



Review

Hybrid and single feedstock energy processes for liquid transportation fuels: A critical review

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ABSTRACT

This review provides a detailed account of the key contributions within the energy communities with specific emphasis on thermochemically based hybrid energy systems for liquid transportation fuels. Specifically, the advances in the indirect liquefaction of coal to liquid (CTL), natural gas to liquid (GTL), biomass to liquid (BTL), coal and natural gas to liquid (CGTL), coal and biomass to liquid (CBTL), natural gas and biomass to liquid (BGTL), and coal, biomass, and natural gas to liquid (CBGTL) are presented. This review is the first work that provides a comprehensive description of the contributions for the single-feedstock energy systems and the hybrid feedstock energy systems, for single stand-alone processes and energy supply chain networks. The focus is on contributions in (a) conceptual design, (b) process simulation, (c) economic analysis, (d) heat integration, (e) power integration, (f) water integration, (g) process synthesis, (h) life cycle analysis, (i) sensitivity analysis, (j) uncertainty issues, and (k) supply chain. A classification of the contributions based on the products, as well as different research groups is also provided.

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1. Introduction

The current global energy sector is mostly driven by fossil fuels (i.e., petroleum, coal, and natural gas), with petroleum being the longstanding, primary energy source. The United States Energy Information Administration also projects that petroleum will remain the primary fuel of choice in its various projection cases up to 2035 (Energy Information Administration., 2011). Increasingly though, the sector is faced with challenges over high energy prices, volatility of the global oil market, and the pressure to reduce greenhouse gas (GHG) emissions from fossil fuel consumption. Alternative energy sources such as solar, wind, hydropower, and nuclear still need major technological developments to play a significant role in replacing fossil fuels and abating greenhouse gas emissions. Additionally, uncertainties such as the recent earthquake and tsunami that damaged several nuclear reactors in Japan may have profound impacts on the future of world nuclear power (Energy Information Administration., 2011).

To address some of these challenges, the use of biomass to produce liquid transportation fuels (biofuels) has emerged as a focus of interest since they provide a renewable carbon-based source that can absorb atmospheric CO₂ during photosynthesis (Lynd et al., 2009; NAS, NAE and NRC, 2009; Science & Board, 2008). In the United States transportation sector, which consumes a large majority of the petroleum supply to the country, biofuels can complement and/or replace petroleum, reducing both fuel imports and GHG emissions, provided that the biomass is cultivated sustainably.

Today, corn-based ethanol and soybean-based diesel comprise a majority of the manufactured biofuels. However, their use for fuel production has led to concerns regarding the impact on the price and availability of these feedstocks as sources of food (Lynd et al., 2009). Lignocellulosic plant sources (e.g., corn stover or forest residue) are expected to be a more considerable source of biofuels in the future, though an increase in crop production will be required to generate an appropriate amount of sustainable residue for fuels production (de Fraiture, Giordano, & Liao, 2008; DOE & USDA, 2005; National Research Council, 2008).

In light of the aforementioned challenges, many research efforts have explored alternative, non-petroleum based processes, including thermochemical liquid fuel production from coal, natural gas, and biomass via synthesis gas (syngas) intermediate and conversion to hydrocarbons through the Fischer–Tropsch (FT) reaction. Syngas is produced via natural gas reforming, coal or biomass gasification, and this intermediate opens opportunities of hybrid processes that combine syngas from multiple feedstock sources. Utilizing coal, natural gas, and biomass as carbon sources will shift dependence away from petroleum and the produced FT liquids can be readily integrated with the current fuel market. The abundance of coal, combined with recent expansions of natural gas from conventional and unconventional sources, will enhance the security of fuel supply, while the incorporation of biomass in the portfolio of energy processes will help reduce GHG emission figures. In order to compete with petroleum-based fuels, many researchers have pursued efforts to optimize the plant design, technology considerations, as well as multiple products to increase the profitability of the process. It is also important to optimize the utilities usage of the plant (e.g., heat, power, and water), the investment for the heat

exchanger/power recovery network, and recover additional profit in selling utility byproduct.

With the move towards biomass-based fuels, the demand for agricultural or perennial crops will increase, affecting the national and regional withdrawal and consumption of freshwater needed for irrigation. Moreover, the freshwater input for the biorefineries to make up for process losses will add to the consumption figure, putting additional stress on water resources. As an essential resource to various ecosystems and human activities, the demand of freshwater spans across agricultural, industrial, and residential sectors. While the abundance and distributed nature of the supply thus far has kept the price of freshwater relatively low, future population increases and economic developments will intensify the pressure on water resources. In the United States alone, the total national freshwater in 2005 use was 349 billion gallons per day (Bgal/d) (Kenny et al., 2009), and is expected to increase by 25% in 2030 assuming an average population growth scenario of 0.9%/year (Energy Information Administration., 2010). If a large-scale production of biomass for transportation fuels is realized, the freshwater use will exceed the expected 25% and additional measures will have to be employed to minimize the supply-demand gap.

The intensifying stress on water resources prompts efforts to minimize freshwater usage in energy conversion processes. Water is typically used for washing operations, separation processes, steam and power generation, cooling systems, or as a raw material input to the processes. The discharged wastewater needs to be treated before the final disposal to the environment and the treatment processes can be energy intensive (Department of Energy, 2006; Mielke, Anadon, & Narayanamurti, 2010). Thus, the development of approaches to design efficient water networks for industrial processes, minimizing both freshwater consumption and wastewater discharge from the process, are of major importance (Ahmetovic & Grossmann, 2010, 2010a; Grossmann & Martín, 2010; Karuppiiah & Grossmann, 2006).

In addition to process developments for a single plant, studies have also been done that consider a network based approach to identify potential locations of these fuel producing plants. Logistical considerations in transporting the feedstocks and products to and from the plants are taken into account such that the overall cost of production is minimized. The transportation factor for biomass-based systems is especially important due to the diffused nature of biomass resources and its low energy density compared to coal and natural gas, which are more centralized and produced in high amounts. Strategic locations of biorefineries will depend on the regional production of biomass, whether the availability can fulfill a continuous supply of biomass to the plant or not. In hybrid processes where biomass feedstock is combined with coal and/or natural gas, it is important then to investigate the trade-offs of delivering coal, natural gas, and biomass feedstocks in choosing the locations of the hybrid plants.

In this paper, we review and discuss the thermochemical based process designs for the production of liquid transportation fuels from coal, biomass, or natural gas feedstocks. Specifically, studies on the indirect liquefaction of the three feedstocks via syngas intermediate are reviewed to elucidate the contributions already established in literature. The main products considered in this paper include gasoline, diesel, kerosene, methanol, and di-methyl ether (DME), which can be produced using commercially viable

Table 1
List of abbreviations used throughout the review paper.

Acronym	Description
ASU	Air separation unit
ATR	Autothermal reactor
BGTL	Biomass and natural gas to liquid
BIGCC	Biomass integrated gasification combined cycle
BTL	Biomass to liquid
CBGTL	Coal, biomass, and natural gas to liquid
CBTL	Coal and biomass to liquid
CCS	Carbon capture and sequestration
CFD	Computational fluid dynamics
CFMR	Cascading fluidized-bed membrane reactor
CGTL	Coal and natural gas to liquid
CI	Compression ignition
CNG	Compressed natural gas
CSTR	Continuous stirred-tank reactor
CTL	Coal to liquid
DCL	Direct coal liquefaction
DE	Differential evolution
DME	Di-methyl ether
FT	Fischer–Tropsch
FTS	Fischer–Tropsch synthesis
GA	Genetic Algorithm
GHG	Greenhouse gas
GIS	Geographic information system
GTL	Gas to liquid
IGCC	Integrated gasification combined cycle
LCA	Life cycle analysis
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MARKAL	Market allocation
MILP	Mixed-integer linear optimization
MINLP	Mixed-integer nonlinear optimization
OCM	Oxidative coupling of methane
PFR	Plug flow reactor
SNG	Synthetic natural gas
SWOT	Strengths, weaknesses, opportunities, and threats
TAPS	Trans-Alaska Pipeline System
TDC	Thermal diffusion column
<i>Units</i>	
Bgal/d	Billion gallons per day
BPD	Barrels per day
GGE	Gallon of gasoline equivalent
TPD	Tons per day

technologies. Comprehensive reviews of the challenges and opportunities in energy research and advances in energy process systems engineering (Liu, Georgiadis, & Pistikopoulos, 2011) have recently appeared.

The review will initially detail the single-type feedstock designs in which only one type of feedstock: coal, natural gas, or biomass is used as a raw material for liquid fuel production (i.e., coal to liquids (CTL), natural gas to liquids (GTL), and biomass to liquids (BTL), respectively). Hybrid feedstock energy processes using a combination of two or three feedstocks will then be discussed to highlight the strategic and synergistic benefits of a mixture of different feedstocks (i.e., coal and natural gas to liquids (CGTL), coal and biomass to liquids (CBTL), natural gas and biomass to liquids (BGTL), and coal, biomass, and natural gas to liquids (CBGTL)). Finally, key challenges and opportunities in the field are outlined. Table 1 lists all the abbreviations used in this review paper.

2. Single feedstock energy processes

Table 2 classifies the contributions for single feedstock energy processes, namely coal to liquids (CTL), natural gas to liquids (GTL), and biomass to liquids (BTL) processes into two general categories, contributions on (a) stand-alone processes, and (b) network-based energy supply chain analyses. In the first category, research publications that investigate the development of a single plant process are tabulated according to their specific contributions. In this paper,

we focus on the following contributions: (i) conceptual design, (ii) process simulation, (iii) economic analysis, (iv) heat integration, (v) power integration, (vi) water integration, (vii) process synthesis, (viii) life cycle analysis, (ix) sensitivity analysis, and (x) uncertainty considerations. For example, research publications listed under (i) propose conceptual designs of the coal, natural gas, or biomass energy processes, and the publications that include simulations and economic analysis of the proposed process are noted under (ii) and (iii), respectively. Categories (iv), (v), and (vi) outline publications that, along with the proposed energy conversion process, also include frameworks to integrate heat, power, or water networks in their approach. Research works that consider a superstructure of technologies and conversion routes of feedstock to products, and identify the optimal plant topology based on an optimization framework are categorized under the process synthesis category (vii). Variations of parameter inputs in the design, simulation, and optimization of energy processes are generally taken into account via sensitivity analysis (ix) and design, simulation, and optimization under uncertainty (x). Finally, the proposed process' environmental performance is measured by the greenhouse gas emissions either on a well-to-wheel basis or on a single plant basis.

In the second category, coal, natural gas, or biomass energy processes are considered in a supply chain network, where the logistical considerations for the upstream and/or downstream processes of the plant such as the feedstock acquisition, transportation, and product transportation, are taken into account. The key question in the problem formulation is where to locate the plant facilities with respect to the regional constraints (e.g., feedstock availabilities, demand amount, and transportation infrastructure) that will minimize the overall cost of fuel production. Solutions of such problems include the proposed locations where the facilities should be built and the flow rate and costs of each interconnection between the feedstock and product nodes with the selected facilities.

Table 3 organizes the contributions listed in Table 2 based on the products of the energy processes. The five main liquid products from the thermochemically based, indirect liquefaction of the feedstocks are gasoline, diesel, kerosene, methanol, and dimethyl ether (DME). Other products listed on the table (i.e., electricity, hydrogen, liquefied petroleum gas (LPG), etc.) are co-products of the reviewed processes.

From Table 2, it is readily observed that the BTL system has recently attracted much attention as biomass is a renewable energy source that can potentially play a bigger role in the future. Across the three single feedstock energy systems, water integration has not been a focus of attention, although water resource consideration will have to be taken into account especially if biomass production will be significantly expanded in the future. As biomass feedstocks have lower energy density compared to coal and natural gas, reducing the cost of biomass energy systems is still a challenge. However, the GHG emissions figure from BTL systems is lower than CTL and GTL systems, elucidating a trade off between economic and environmental performances of CTL, GTL, and BTL systems.

Several studies provide comparisons between the three processes to evaluate the marketability, economic and environmental performances of each system. An overview of GTL, CTL, and BTL technologies can be found in Gill, Tsolakis, Dearn, and Fernández (2011). Erturk (2011) performed an economic analysis on each system and identified key factors that determine the profitability of the system under various market conditions. Vliet et al. (2009) compared the carbon and energy balances of 14 different Fischer–Tropsch (FT) fuel production and found that BTL produces fuel at the highest cost, and CTL and GTL, without carbon capture and sequestration, will emit GHG more than conventional oil. Ren, Daniels, Patel, and Blok (2009) studied 24 routes of GTL, CTL, and BTL and estimated the production costs for 2030–2050 using

Table 2

CTL, GTL, and BTL contributions on stand-alone processes and energy supply chain networks. The numerical figures refer to the reference list at the end of this paper.

Component	CTL	GTL	BTL
<i>Stand-alone systems</i>			
Conceptual design	Sudiro, Bertuccio, Ruggeri, and Fontana (2008), Li, Gao, Chang, Liu, and Pistikopoulos (2010), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu, Zu, Hao, Li, and Liu (2010), Liu, Pistikopoulos, and Li (2009), Lamprecht, Nel, and Leckel (2010), Liu, Pistikopoulos, and Li (2010b), Liu, Pistikopoulos, and Li (2010a), Williams, Larson, Liu, and Kreutz (2009), Kreutz et al. (2008), Liu, Larson, Williams, Kreutz, and Guo (2011), Williams, Liu, Kreutz, and Larson (2011), Chen, Adams, and Barton (2011b), Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Adams and Barton (2011a), Chen, Adams, and Barton (2011a), Adams and Barton (2011b), Zhou, Hu, Li, and Zhou (2008), Huffman (2011), Zhou et al. (2009), Guang-jian, Zheng, Ming-hua, and Wei-dou (2010), Larson and Tingjin (2003), Han, Zhang, Ying, and Fang (2009), Cocco, Pettinau, and Cau (2006), Jun-ling, Hao, Zharr Cheng, and Zhi hong (2002), Sun, Jin, Gao, and Han (2010), Cau, Carapelluci, and Cocco (1997), Lin, Jin, Gao, and Han (2011), Dillerop, van der Berg, and van der Ham (2010), Gao, Jin, Liu, and Zheng (2004), Lin, Jin, Gao, and Han (2010)	Hao et al. (2008), Bao, El-Halwagi, and Elbashir (2010), Iandoli and Kjelstrup (2007), Kim, Jun, Joo, Han, and Song (2009), Hall (2005), Ha, Bae, Woo, and Jun (2010), Lee, Lim, Kim, and Han (2009), Suzuki, Sasaki, and Kojima (1996), Gao et al. (2008), Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Heimel and Lowe (2009), Zhou et al. (2009), Peng, Wang, Toseland, and Tij (1999), Bin, Hingguang, and Lin (2008), Horstman, Abata, Keith, and Oberito (2005)	Larson, Jin, and Celik (2009), Laser, Jin, Jayawardhana, Dale, and Lynd (2009), Tock, Gassner, and Maréchal (2010), Sues, Jurascik, and Ptasiński (2010), Manganaro et al. (2011), Hamelinck, Faaij, Uil, and Boerrigter (2004), Perales, Valle, Ollero, and Barea (2011), Tijmensen, Faaij, Hamelinck, and Hardeveld (2002), Bridgwater and Double (1991), Swanson, Platon, Satrio, and Brown (2010), Clausen, Elmegaard, and Houbak (2010), Sharma, Sarker, and Romagnoli (2011), Renó et al. (2011), Bao, Ng, Tay, Gutiérrez, and El-Halwagi (2011), Sammons, Yuan, Eden, Aksoy, and Cullinan (2008), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Seiler, Hohwiller, Imbach, and Luciani (2010), Kumabe et al. (2008), Ju et al. (2009), Chang, Fu, and Luo (2012), Hamelinck and Faaij (2002), Clausen, Houbak, and Elmegaard (2010), Van Rens, Huisman, Lathouder, and Cornelissen (2011), Zhang, Solli, Hertwich, Tian, and Zhang (2009), Kim, Han, and Yoon (2010), Zhang, Xiao, and Shen (2009), He and Zhang (2011), Ng and Sadhukkan (2011), Li, Hong, Gao, and Jin (2008), Xiao, Shen, Zhang, and Gu (2009), Mignard and Pritchard (2008), Mignard and Pritchard (2008), Williams, Larson, Katofsky, and Chen (1995), Sarkar, Kumar, and Sultana (2011), De Kam, Morey, and Tiffany (2009), Kou and Zhao (2011), Cucek, Martin, Grossmann, and Kravanja (2011), Zwart and Boerrigter (2005)
Process simulation	Sudiro et al. (2008), Li, Gao, et al. (2010), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Chen et al. (2011b), Chen et al. (2011a), Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Zhou et al. (2009), Guang-jian et al. (2010), Larson and Tingjin (2003), Han et al. (2009), Cocco et al. (2006), Sun et al. (2010), Lin et al. (2011), Gao et al. (2004), Lin et al. (2010)	Hao et al. (2008), Bao et al. (2010), Iandoli and Kjelstrup (2007), Kim et al. (2009), Ha et al. (2010), Lee et al. (2009), Gao et al. (2008), Dillerop et al. (2010), Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Heimel and Lowe (2009), Liu, Williams, Larson, and Kreutz (2011b), Zhou et al. (2009), Peng et al. (1999), Bin et al. (2008)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Sues et al. (2010), Manganaro et al. (2011), Hamelinck et al. (2004), Perales et al. (2011), Tijmensen et al. (2002), Bridgwater and Double (1991), Swanson et al. (2010), Clausen, Elmegaard, et al. (2010), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Kumabe et al. (2008), Ju et al. (2009), Chang et al. (2012), Hamelinck and Faaij (2002), Clausen, Houbak, et al. (2010), Van Rens et al. (2011), Zhang, Solli, et al. (2009), Zhang, Xiao, et al. (2009), He and Zhang (2011), Ng and Sadhukkan (2011), Li et al. (2008), Xiao et al. (2009), Wu, Wu, and Wang (2006), Williams et al. (1995), De Kam et al. (2009), Kou and Zhao (2011), Zwart and Boerrigter (2005)
Economic analysis	Li, Gao, et al. (2010), Liu, Gerogiorgis, and Pistikopoulos (2007), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Liu et al. (2009), Liu et al. (2010b), Liu et al. (2010a), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Chen et al. (2011b), Chen et al. (2011a), Larson et al. (2010), Larson, Fiorese, et al. (2009), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Erturk (2011), Vliet et al. (2009), Zhou et al. (2009), Larson and Tingjin (2003), Cocco et al. (2006), Jun-ling et al. (2002), Lin et al. (2011), Lin et al. (2010)	Bao et al. (2010), Hall (2005), Lee et al. (2009), Suzuki et al. (1996), Dillerop et al. (2010), Heimel and Lowe (2009), Zhou et al. (2009), Erturk (2011), Vliet, Faaij, and Turkenburg (2009)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Hamelinck et al. (2004), Perales et al. (2011), Tijmensen et al. (2002), Bridgwater and Double (1991), Swanson et al. (2010), Clausen, Elmegaard, et al. (2010), Sharma et al. (2011), Henrich, Dahmen, and Dinjus (2009), Sunde, Brekke, and Solberg (2011), Bao et al. (2011), Tay, Ng, Sammons, and Eden (2011), Giarola, Zamboni, and Bezzo (2011), Bai, Hwang, Kang, and Ouyang (2011), Bowling, Ortega, and El-Halwagi (2011), Parker et al. (2010), Huang, Chen, and Fan (2010), Aksoy, Cullinan, Sammons, and Eden (2008), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Larson et al. (2010), Kumabe et al. (2008), Ju et al. (2009), Hamelinck and Faaij (2002), Clausen, Houbak, et al. (2010), Kim et al. (2010), He and Zhang (2011), Ng and Sadhukkan (2011), Xiao et al. (2009), Erturk (2011), Vliet et al. (2009), Dal-Mas, Giarola, Zamboni, and Bezzo (2011), Amigun, Gorgens, and Knoetze (2010), Leduc, Schwab, Dotzauer, Schmid, and Obersteiner (2008), Leduc, Schmid, Obersteiner, and Riahi (2009), Leduc, Lundgren, Franklin, and Dotzauer (2010), Mignard and Pritchard (2008), Williams et al. (1995), Sarkar et al. (2011), Kou and Zhao (2011), Cucek et al. (2011),

Table 2 (Continued)

Component	CTL	GTL	BTL
			Marvin, Schmidt, Benjaafar, Tiffany, and Daoutidis (2012), Terrados, Almonacid, and Higuera (2009), Akgul, Zamboni, Bezzo, Shah, and Papageorgiou (2011), van Dyken, Bakken, and Skjelbred (2010), Rentizelas and Tatsiopoulos (2010), Rentizelas, Tatsiopoulos, and Tolis (2009), Eksioğlu, Acharya, Leightley, and Arora (2009), Eksioğlu, Li, Zhang, Sokhansanj, and Petrolia (2010), Zamboni, Shah, and Bezzo (2009), Dunnnett, Adjiman, and Shah (2008), Marti and Gonzalez (2010), Panichelli and Gnansounou (2008), Zhang, Johnson, and Sutherland (2011), An, Wilhelm, and Searcy (2011b), Gan and Smith (2011), Leduc, Starfelt, et al. (2010), Hacatoglu, McLellan, and Layzell (2011), Cherubini (2010b), Kocoloski, Griffin, and Matthews (2011), Cucek, Lam, Klemes, Varbanov, and Kravanja (2010), Zwart and Boerrigter (2005)
Heat integration	Sudiro et al. (2008), Li, Gao, et al. (2010), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Liu et al. (2009), Liu et al. (2010b), Liu et al. (2010a), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Chen et al. (2011b), Chen et al. (2011a), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2009), Guang-jian et al. (2010), Larson and Tingjin (2003), Cocco et al. (2006), Sun et al. (2010), Lin et al. (2011), Gao et al. (2004), Lin et al. (2010)	Bao et al. (2010), landoli and Kjelstrup (2007), Gao et al. (2008), Dillerop et al. (2010), Zhou et al. (2009), Bin et al. (2008)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Sues et al. (2010), Hamelinck et al. (2004), Perales et al. (2011), Tijmensen et al. (2002), Swanson et al. (2010), Clausen, Elmegaard, et al. (2010), Sharma et al. (2011), Renó et al. (2011), Tay et al. (2011), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Ju et al. (2009), Hamelinck and Faaij (2002), Clausen, Houbak, et al. (2010), Van Rens et al. (2011), Zhang, Solli, et al. (2009), Kim et al. (2010), He and Zhang (2011), Ng and Sadhukkan (2011), Li et al. (2008), Xiao et al. (2009), Leduc et al. (2008), Leduc, Lundgren, et al. (2010), Williams et al. (1995), De Kam et al. (2009), Cucek et al. (2011), Rentizelas and Tatsiopoulos (2010), Rentizelas, Tatsiopoulos, et al. (2009), Marti and Gonzalez (2010), Leduc, Starfelt, et al. (2010),
Power integration	Sudiro et al. (2008), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Liu et al. (2009), Liu et al. (2010b), Liu et al. (2010a), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2009), Guang-jian et al. (2010), Larson and Tingjin (2003), Cocco et al. (2006), Sun et al. (2010), Lin et al. (2011), Gao et al. (2004), Lin et al. (2010)	Bao et al. (2010), landoli and Kjelstrup (2007), Gao et al. (2008), Zhou et al. (2009), Bin et al. (2008)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Sues et al. (2010), Hamelinck et al. (2004), Perales et al. (2011), Tijmensen et al. (2002), Swanson et al. (2010), Clausen, Elmegaard, et al. (2010), Sharma et al. (2011), Renó et al. (2011), Tay et al. (2011), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Kumabe et al. (2008), Ju et al. (2009), Hamelinck and Faaij (2002), Van Rens et al. (2011), Zhang, Solli, et al. (2009), Kim et al. (2010), He and Zhang (2011), Ng and Sadhukkan (2011), Li et al. (2008), Williams et al. (1995), De Kam et al. (2009), Rentizelas and Tatsiopoulos (2010), Rentizelas, Tatsiopoulos, et al. (2009), Marti and Gonzalez (2010), Leduc, Starfelt, et al. (2010)
Water integration		Bao et al. (2010)	Cucek et al. (2011)
Process synthesis	Li, Gao, et al. (2010), Liu et al. (2009), Liu et al. (2010b), Liu et al. (2010a), Chen et al. (2011b), Chen et al. (2011a)		Sharma et al. (2011), Bao et al. (2011), Sammons et al. (2008), Tay et al. (2011), Giarola et al. (2011), Kim et al. (2010), Cucek et al. (2011)
Life cycle analysis	Li, Gao, et al. (2010), Liu et al. (2010b), Jaramillo, Griffin, and Matthews (2008), Jaramillo, Samaras, Wakeley, and Meisterling (2009), Dooley, Dahowski, and Davidson (2009), Xunmin, Yan, and Xiliang (2010), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Larson et al. (2010), Larson, Fiorese, et al. (2009), Vliet et al. (2009), Larson and Tingjin (2003), Zhang and Huang (2007)	Hao, Wang, Song, Li, and Ouyang (2010), Jaramillo et al. (2008), Jaramillo et al. (2009), Vliet et al. (2009)	Sharma et al. (2011), Sunde et al. (2011), Renó et al. (2011), Giarola et al. (2011), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Larson et al. (2010), Xiao et al. (2009), Vliet et al. (2009), Ahlgren et al. (2008), Dowaki and Genchi (2009), Wu et al. (2006), Joelsson and Gustavsson (2010), Higo and Dowaki (2010), Cherubini and Jungmeier (2010), Williams et al. (1995), Kou and Zhao (2011), Wahlund, Yan, and Westermarck (2004), Hoefnagels, Smeets, and Faaij (2010), Cucek et al. (2010)
Sensitivity analysis	Sudiro et al. (2008), Li, Gao, et al. (2010), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Liu et al. (2009), Williams et al. (2009), Kreutz et al. (2008), Liu, Larson, et al. (2011), Williams et al. (2011), Sudiro and Bertuccio (2007), Chen et al. (2011b), Chen et al. (2011a), Zhou et al. (2009), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008),	Hao et al. (2008), Bao et al. (2010), Kim et al. (2009), Ha et al. (2010), Lee et al. (2009), Suzuki et al. (1996), Sudiro and Bertuccio (2007), Zhou et al. (2009), Peng et al. (1999), Dillerop et al. (2010), Liu et al. (2011b), Vliet et al. (2009)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Sues et al. (2010), Manganaro et al. (2011), Hamelinck et al. (2004), Tijmensen et al. (2002), Williams et al. (2009), Kreutz et al. (2008), Clausen, Elmegaard, et al. (2010), Sharma et al. (2011), Liu, Larson, et al. (2011), Williams et al. (2011), Seiler et al. (2010), Kumabe et al. (2008), Ju et al. (2009), Chang et al. (2012), Hamelinck and Faaij (2002), Clausen, Houbak, et al. (2010), Zhang, Solli, et al. (2009), Zhang, Xiao, et al. (2009), He and Zhang (2011), Ng and Sadhukkan (2011), Li et al. (2008), Mignard and Pritchard (2008), Vliet et al. (2009), Larson et al. (2010),

Table 2 (Continued)

Component	CTL	GTL	BTL
	Larson and Tingjin (2003), Han et al. (2009), Lin et al. (2011), Dillerop et al. (2010), Lin et al. (2010), Liu et al. (2007), Vliet et al. (2009), Larson et al. (2010), Larson, Fiorese, et al. (2009)		Bai et al. (2011), Parker et al. (2010), Huang et al. (2010), Amigun et al. (2010), Leduc et al. (2008), Leduc et al. (2009), Leduc, Lundgren, et al. (2010), Ahlgren et al. (2008), Joelsson and Gustavsson (2010), Kim, Realff, Lee, Whittaker, and Furtner (2011), Williams et al. (1995), Sarkar et al. (2011), Kou and Zhao (2011), Cucek et al. (2011), Marvin et al. (2012), Panichelli and Gnansounou (2008), Kocoloski et al. (2011), Cucek et al. (2010), Zwart and Boerrigter (2005)
Uncertainty	Mantripragada and Rubin (2011b), Liu et al. (2010a),	Khalilpour and Karimi (2011)	Dal-Mas et al. (2011), Kim, Realff, and Lee (2011)
Network-based analyses			
Supply chain and strategic planning	Li, Gao, et al. (2010), Liu et al. (2007)	Khalilpour and Karimi (2011)	Sharma et al. (2011), Henrich et al. (2009), Sammons et al. (2008), Giarola et al. (2011), Meehan and McDonnell (2010), Bai et al. (2011), Bowling et al. (2011), Ravula, Grisso, and Cundiff (2008), Parker et al. (2010), Huang et al. (2010), Aksoy et al. (2008), Dal-Mas et al. (2011), Amigun et al. (2010), Leduc et al. (2008), Leduc et al. (2009), Leduc, Lundgren, et al. (2010), Kim, Realff, Lee, Whittaker, et al. (2011), Kim, Realff, and Lee (2011), Marvin et al. (2012), Terrados et al. (2009), Akgul et al. (2011), van Dyken et al. (2010), Rentizelas and Tatsiopoulos (2010), Rentizelas, Tatsiopoulos, et al. (2009), Eksioglu et al. (2009), Eksioglu et al. (2010), Zamboni, Shah, et al. (2009), Dunnett et al. (2008), Marti and Gonzalez (2010), Panichelli and Gnansounou (2008), Zhang et al. (2011), An et al. (2011b), Gan and Smith (2011), Leduc, Starfelt, et al. (2010), Hacatoglu et al. (2011), Cherubini (2010b), Kocoloski et al. (2011), Cucek et al. (2010)

Note: The list of references included in this table does not include studies on subcomponents on the CTL, GTL, and BTL processes (e.g., gasifier operation, catalyst systems, etc.). These studies, however, are mentioned within the text.

a Monte Carlo method. Finally, Ren and Patel (2009) compared the calculations on energy use and CO₂ emissions of GTL, CTL, and BTL processes.

The distinct difference of the distribution between coal, natural gas, and biomass feedstock production poses an interesting contrast between CTL, GTL, and BTL systems in a supply chain framework. Since large quantities of coal and natural gas are produced in a centralized manner and the transportation infrastructures (e.g., railways, pipelines, etc.) are largely in place, the logistics of coal and natural gas delivery to potential locations of CTL and GTL plants are well established. Biomass production, however, is more diffused in nature and is done in smaller quantities. The distance limitation of biomass transportation, which is done mostly by truck, adds another restriction to the selection of BTL facility locations. As a result, much more attention has been given to the supply chain and strategic planning of BTL systems compared to CTL and BTL systems.

In addition to contributions of academic papers, we highlight several reports that outlined detailed information on coal to fuels (Bechtel, 1992; National Energy Technology Laboratory, 2007a, 2009; NAS, NAE and NRC, 2009), coal and natural gas to electricity (National Energy Technology Laboratory, 2007b), coal to fuels and electricity (Bechtel Corp and Global Energy Inc. and Nexant Inc., 2003), biomass to fuels (Jones & Zhu, 2009; National Energy Technology Laboratory, 2009; NAS, NAE and NRC, 2009; Phillips, Tarud, Biddy, & Dutta, 2011), biomass to fuels and electricity (Bechtel, 1998), and biomass to hydrogen (Spath et al., 2005) processes whose components can be incorporated into academic researches. Note that these reports are not reviewed in this paper.

2.1. Coal to liquids (CTL)

Due to its abundant known reserves, coal is an attractive alternative to petroleum as energy source. The conversion of coal to liquid fuels can take place via two main routes, namely direct or indirect

coal liquefaction. The latter option, more specifically gasification-based, Fischer–Tropsch (FT) conversion to liquid fuels, is currently more technically and commercially established, and is reviewed in this paper.

2.1.1. Process description

A typical CTL plant is shown in Fig. 1 (reprinted from Kreutz et al., 2008). In the CTL plant, a coal feedstock is initially gasified at high temperatures to produce a raw synthesis gas (syngas) containing H₂, CO, CO₂, and H₂O as the four major components. It has been shown that these four species will exist in relative concentrations that are close to the thermodynamic equilibrium dictated by the water–gas–shift reaction (Li, Grace, Watkinson, & Ergüdenler, 2001; Yuehong, Hao, & Zhihong, 2006). These compositions will also vary depending on the coal gasifier type (Jarungthammachote & Dutta, 2008) and a model on the coal gasifier based on a variety of gasifier types is included in Baliban et al. (2010). In addition to these four species, light C₁ and C₂ hydrocarbons and acidic gas species (e.g., NH₃, H₂S, HCl) will generally be found in concentrations far above their equilibrium values. Prior to entering the FT units, these acidic species must be stripped from the syngas to prevent poisoning of the FT catalyst. This cleaning unit generally utilizes either physical or chemical absorption to remove the acid gas which is subsequently directed to a treating facility (e.g., a Claus plant) to recover the sulfur. If desired, the CO₂ in the syngas can also be separated using physical or chemical absorption using either “co-capture” of the CO₂ and other acid gases or separate capture of these two gas streams. A two-stage absorption framework that can capture the sulfur-rich gases and the CO₂ separately is beneficial when a pure CO₂ stream is required for either (i) process recycle or (ii) sequestration.

A 2:1 ratio of H₂ to CO in the synthesis gas is generally desired to maximize the conversion of CO in the FT reactor. However, the composition of the syngas exiting the gasifier will have a ratio that is less than one due to the low hydrogen content in coal. The

Table 3
Single feedstock energy process systems organized by product type.

Products	CTL	GTL	BTL
Gasoline	Sudiro et al. (2008), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Lamprecht et al. (2010), Huffman (2011), Bechtel (1992), Bechtel Corp and Global Energy Inc. and Nexant Inc. (2003)	Bao et al. (2010), Heimel and Lowe (2009), Hall (2005), Dillerop et al. (2010), Suzuki et al. (1996)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Sues et al. (2010), Tijmensen et al. (2002), Bridgwater and Double (1991), Swanson et al. (2010), Bao et al. (2011) Kim, Realff, Lee, Whittaker, et al. (2011), Kim, Realff, and Lee (2011), Joelsson and Gustavsson (2010), Sarkar et al. (2011), Bechtel (1998), Zwart and Boerrigter (2005)
Diesel	Sudiro et al. (2008), Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Lamprecht et al. (2010), Huffman (2011), Bechtel (1992), Bechtel Corp and Global Energy Inc. and Nexant Inc. (2003)	Bao et al. (2010), Heimel and Lowe (2009), Hall (2005), Lee et al. (2009)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Tock et al. (2010), Sues et al. (2010), Hamelinck et al. (2004), Tijmensen et al. (2002), Bridgwater and Double (1991), Swanson et al. (2010), Sharma et al. (2011), Bowling et al. (2011), Parker et al. (2010), Ahlgren et al. (2008) Kim, Realff, Lee, Whittaker, et al. (2011), Kim, Realff, and Lee (2011), Joelsson and Gustavsson (2010), Wu et al. (2006), Sarkar et al. (2011), Hacatoglu et al. (2011), Bechtel (1998), Zwart and Boerrigter (2005)
Kerosene			Tijmensen et al. (2002)
Methanol	Li, Gao, et al. (2010), Liu et al. (2009), Liu et al. (2010b), Liu et al. (2007), Cau et al. (1997), Lin et al. (2011), Gao et al. (2004) Guang-jian et al. (2010), Liu et al. (2010a), Larson and Tingjin (2003), Sun et al. (2010),	Lee et al. (2009), Gao et al. (2008)	Tock et al. (2010), Sues et al. (2010), Bridgwater and Double (1991), Renó et al. (2011), Kumabe et al. (2008), Clausen, Houbak, et al. (2010), Amigun et al. (2010), Leduc et al. (2009), Van Rens et al. (2011), Zhang, Xiao, et al. (2009), Ng and Sadhukkan (2011), Li et al. (2008), Leduc et al. (2008), Dowaki and Genchi (2009), Leduc, Lundgren, et al. (2010), Xiao et al. (2009), Liu et al. (2007), Joelsson and Gustavsson (2010), Williams et al. (1995), Sarkar et al. (2011)
Dimethyl ether	Zhang and Huang (2007), Han et al. (2009), Larson and Tingjin (2003), Cocco et al. (2006), Jun-ling et al. (2002)	Lee et al. (2009), Peng et al. (1999), Bin et al. (2008), Horstman et al. (2005), Zhou et al. (2009)	Larson, Jin, et al. (2009), Tock et al. (2010), Clausen, Elmegaard, et al. (2010), Tay et al. (2011), Ahlgren et al. (2008), Ju et al. (2009), Chang et al. (2012), Van Rens et al. (2011), Zhang, Solli, et al. (2009), Kim et al. (2010), Dowaki and Genchi (2009), Joelsson and Gustavsson (2010) Wu et al. (2006), Sarkar et al. (2011)
Electricity ^a	Mantripragada and Rubin (2009), Mantripragada and Rubin (2011b), Mantripragada and Rubin (2011a), Yu et al. (2010), Liu et al. (2009), Liu et al. (2010b), Liu et al. (2007), Guang-jian et al. (2010), Liu et al. (2010a), Larson and Tingjin (2003), Cocco et al. (2006), Sun et al. (2010), Cau et al. (1997), Lin et al. (2011), Gao et al. (2004)	Gao et al. (2008), Bin et al. (2008), Zhou et al. (2009)	Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Sues et al. (2010), Hamelinck et al. (2004), Swanson et al. (2010), Clausen, Elmegaard, et al. (2010), Sharma et al. (2011), Tay et al. (2011), Kim et al. (2010), Ng and Sadhukkan (2011), Li et al. (2008), Liu et al. (2007), Hacatoglu et al. (2011), De Kam et al. (2009), Rentizelas and Tatsiopoulous (2010), Rentizelas, Tatsiopoulous, et al. (2009), Marti and Gonzalez (2010), Leduc, Starfelt, et al. (2010), Cucek et al. (2010), Bechtel (1998)
Ethanol ^a			Laser, Jin, et al. (2009), Perales et al. (2011), Bridgwater and Double (1991), Sharma et al. (2011), Bai et al. (2011), Giarola et al. (2011), Huang et al. (2010), Parker et al. (2010), Dal-Mas et al. (2011), He and Zhang (2011), Cherubini and Jungmeier (2010), De Kam et al. (2009), Kou and Zhao (2011), Cucek et al. (2011), Marvin et al. (2012), Akgul et al. (2011), Eksioglu et al. (2009), Eksioglu et al. (2010), Zamboni, Shah, et al. (2009), Dunnett et al. (2008), An et al. (2011b), Gan and Smith (2011), Leduc, Starfelt, et al. (2010), Kocoloski et al. (2011), Cucek et al. (2010)
LPG ^a	Sudiro et al. (2008), Yu et al. (2010), Lamprecht et al. (2010)	Bao et al. (2010)	
Hydrogen ^a			Larson, Jin, et al. (2009), Laser, Jin, et al. (2009), Sues et al. (2010), Van Rens et al. (2011), Williams et al. (1995)
SNG ^a	Sudiro et al. (2008)		Laser, Jin, et al. (2009), Sues et al. (2010), Zwart and Boerrigter (2005)
Crude products ^a		Hao et al. (2008), landoli and Kjelstrup (2007), Kim et al. (2009), Ha et al. (2010)	Tay et al. (2011)
Other ^a	Heat (Sun et al., 2010), Carbon nanotubes (Huffman, 2011)	Ethylene (Hall, 2005)	Heat (De Kam et al., 2009; Leduc et al., 2008; Leduc, Lundgren, et al., 2010; Ng & Sadhukkan, 2011; Sues et al., 2010), Rentizelas and Tatsiopoulous (2010), Rentizelas, Tatsiopoulous, et al. (2009), Marti and Gonzalez (2010), Leduc, Starfelt, et al. (2010)), Animal feed protein (Dale, Allen, Laser, & Lynd, 2009; Laser, Jin, et al., 2009), Succinic acid, propanediol (Sharma et al., 2011), Ammonia (Sarkar et al., 2011)

^a Dimethyl carbonate, LPG (liquefied petroleum gas), electricity, and hydrogen are byproducts of the processes in the cited literatures and are not reviewed in this paper.

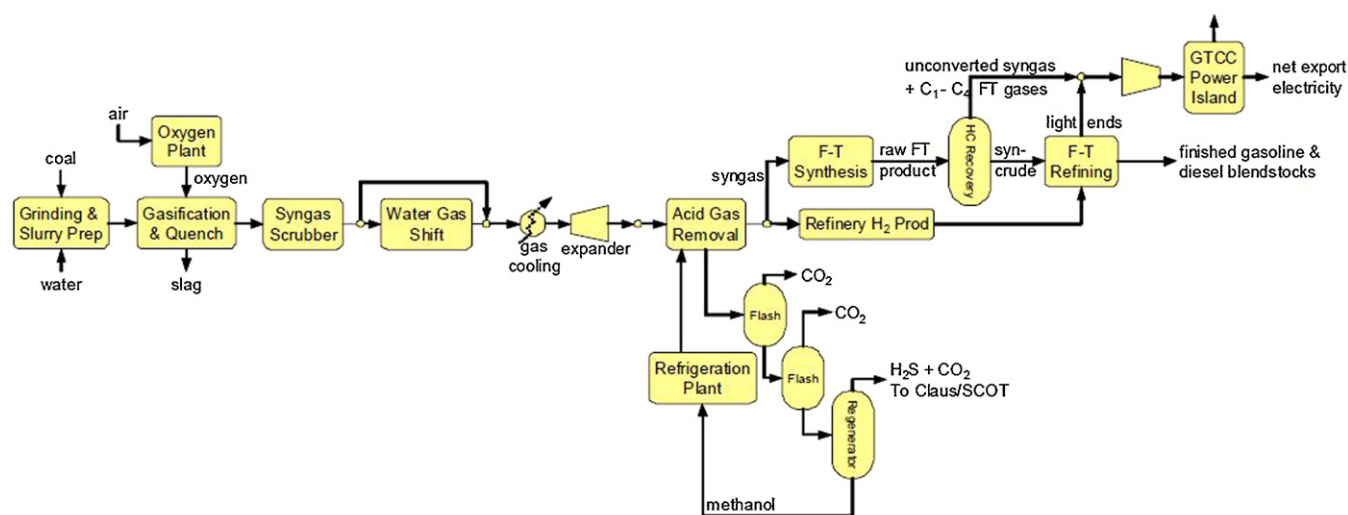


Fig. 1. Coal to liquids process flowsheet (reprinted from Kreutz, Larson, Liu, & Williams, 2008).

water-gas-shift reaction is employed to adjust the $H_2:CO$ ratio by either (i) adding steam and using the forward water-gas-shift reaction or (ii) adding H_2 and using the reverse water-gas-shift reaction. The catalyst used in the water-gas-shift reactor is generally tolerant to the presence of sour gases, so this reaction may occur upstream of the cleaning units at higher temperatures. The products from the FT reactor will be (1) a synthetic blend of hydrocarbons ranging from C_1 to C_{30+} and (2) a heavy wax stream. The composition of the hydrocarbon blend and the ratio of hydrocarbon blend to heavy wax is dependent on the choice of temperature, catalyst, and design of the FT reactor. The effluent from the FT reactor can be upgraded to fuel-quality products using a distillation column, a wax hydrocracker, hydrotreaters, isomerization units, and an alkylation unit (Bechtel, 1992, 1998).

2.1.2. Literature review

The following studies outline the fundamental concepts and several variations of the CTL technologies. Liu, Shi, and Li (2010) and Jianguo et al. (2009) provided a general introduction of CTL and its development in China, specifying that CTL facilities can either be stand-alone or coupled with an integrated gasification combined cycle (IGCC) power plants. Lu and Lee (2007) investigated the effect of H_2/CO ratio in the syngas feed stream for FT synthesis for CTL and GTL applications. Lamprecht et al. (2010) described a conceptual design of a fixed-bed dry bottom coal gasification system for CTL applications with low-rank coals. Leckel (2007) reported experimental results on low-temperature FT wax derived from coal, showing that CTL diesel product is of high quality. Following up on the first study, Leckel (2011) presented experimental results on high-temperature FT distillates. Huffman (2011) proposed the incorporation of a catalytic dehydrogenation step into a CTL process that converts the light C_1 – C_4 products from the FT synthesis to hydrogen, which is recycled to the syngas feed stream in order to reduce CO_2 emissions. The concept is illustrated by calculations based on an experimental Fischer–Tropsch Synthesis (FTS) system, which shows a potentially drastic reduction in CO_2 emissions and water usage of the FTS process. These experiments suggest that CTL fuel products can compete and be fully integrated in the fuel market.

Expanding on the CTL process, coal-based polygeneration systems have also been studied due to the increased economic performance when other products, such as electricity and alternative fuels (e.g., methanol, dimethyl ether (DME), hydrogen), are simultaneously produced along with the FT fuels (Yamashita &

Barreto, 2005). Zheng, Weidou, Hongtao, and Linwei (2003) provided an overview of benefits for polygeneration systems in China. Hongtao, Zheng, Weidou, Larson, and Tingjin (2003) reported a case study of coal gasification based energy system in China. Hao, Dong, Yang, Xu, and Li (2007) gave an overview of a co-generation system, in which an IGCC system is coupled with FT synthesis. Sudiro et al. (2008) studied the coupling of an air-blown coal gasifier-combustor system with a CTL process to improve process performances, reducing the consumption of high-purity oxygen, and CO_2 emissions. A methane removal technology is incorporated into the process design prior to the FT conversion, resulting in a co-production of synthetic natural gas (SNG) along with gasoline, diesel, and LPG. When compared to the conventional CTL system, they found that the coupled system has a higher yield, plant efficiency and reduced CO_2 emissions. Mantripragada and Rubin (2009, 2011b) studied the performance of two CTL systems, one that produces only liquid fuels and one that co-produces electricity, simulated with Aspen Plus. They found that the co-production of fuels and electricity yields better economic performance with the given prices of CO_2 capture and emissions. Mantripragada and Rubin (2011a) simulated processes with the GE (slurry) and Shell (dry-feed) gasifiers for both liquid fuels only and co-production of fuels and electricity. The co-production scheme yielded lower liquid fuel cost due to the increased profit from electricity production. Yu et al. (2010) investigated polygeneration processes in which coal is converted to fuels and electricity with carbon capture. Four case studies with varied syngas portions directed to fuels and electricity production were performed and it was found that the best overall efficiency is achieved when the syngas is sent for maximum FT fuel production with electricity generation from tail gas, instead of the cases where the syngas stream is split and sent directly to the combined cycle for electricity generation.

Other studies have focused on the production of liquids using alternative non-FT routes. These studies have strongly focused on either methanol or DME production due to the potential impact that these two liquids can have in the chemical and energy sectors. Cau et al. (1997) explored and developed a conceptual design for the integration of IGCC system with methanol synthesis and CO_2 removal. Carapellucci, Cau, and Cocco (2001) suggested that the integration of the IGCC system with methanol synthesis can enhance the overall plant performance. Larson and Tingjin (2003) developed conceptual process designs for the indirect coal liquefaction to methanol and DME in both once through structure and recycle plant configurations. Cocco et al. (2006) studied an IGCC

power plant configuration that is integrated with DME synthesis, with comparisons for two types of gasifiers, namely the dry-feed and slurry bed entrained flow gasifier. Zhang and Huang (2007) conducted a life cycle analysis (LCA) for coal-based DME as vehicle fuels in China and suggested that DME has less overall emissions compared to CTL diesel. Jun-ling et al. (2002) explored the feasibility of producing DME to utilize excess coal gas in steel works. Han et al. (2009) modeled the conversion of syngas to DME in a slurry bed reactor and compared the prediction with experimental results. Shim, Lee, Yoo, Yun, and Kim (2009) developed a kinetics model for DME synthesis based on Aspen Plus to determine optimal operating conditions. Zhou et al. (2009) combined the syngas from coal gasification and natural gas reforming to achieve the correct C to H ratio for DME synthesis, eliminating the need for a water gas shift reactor to adjust the syngas composition. For an overview of the DME synthesis process from syngas, the reader is directed to Brown, Bhatt, Hsiung, Lewnard, and Waller (1991).

Exergy analyses for coal to liquid systems have been shown in several studies. Gao et al. (2004) and Guang-jian et al. (2010) performed an exergy analysis for a system that co-produces electricity and methanol. Sun et al. (2010) completed an exergy analysis for a system that consumes coke oven gas and coal, producing coking heat, methanol, and electricity. The two gas sources are mixed to achieve the correct syngas composition for methanol synthesis, and the unreacted syngas is sent to a power generation section. Lin et al. (2010) performed an economic analysis for the co-production of methanol and electricity, and Lin et al. (2011) completed a techno-economic evaluation for the polygeneration system with CO₂ recovery.

In addition to the process designs, several studies have focused on an optimization-based process synthesis methods for coal to liquids systems. Liu et al. (2007) developed an approach for poly-generation energy systems, and applied their model to a system that produces methanol and electricity. The multi-period mathematical model allows for capacity expansion, and determines the feedstock and technology chosen for the process. In a subsequent study, Liu et al. (2009) employed optimization approaches to determine the optimal methanol and electricity polygeneration plant design under user-determined scenarios. A superstructure of the polygeneration system is modeled mathematically, resulting in a mixed-integer nonlinear optimization (MINLP) model with an economic objective function. Li, Gao, et al. (2010) considered a coal-derived methanol production for hydrogen vehicles and used an optimization approach to simultaneously optimize the production, product distribution, and hydrogen dispensing, with the objective of improving energy efficiency, environmental impact, and economic behavior. Liu et al. (2010b) developed a multi-objective optimization approach for a methanol and power co-generation system where the objective function includes both economic and environmental measures. The framework allows for multiple feedstocks, but the case study in the paper is a coal-based polygeneration system. The work is extended in Liu et al. (2010a) to incorporate uncertainties in a multiperiod MINLP problem and a decomposition algorithm is used to obtain the solutions.

The CTL technologies have grown to attract policy discussions (Braithwaite, Horst, & Iacobucci, 2010; Fishedick, 2010; Vallentin, 2008a, 2008b; Yingyue, Liping, Changqing, & Hongmei, 2011; Zhao & Gallagher, 2007). However, while showing promise as a viable fuel-producing technology, the standard CTL design does not provide improvements on the overall GHG emissions compared to petroleum-based technologies. In fact, CTL is estimated to increase the total emissions (Dooley et al., 2009; Jaramillo et al., 2008, 2009; Sovacool, Cooper, & Parenteau, 2011; Xunmin et al., 2010). A recent study (Baliban et al., 2010; Elia et al., 2010) has developed a CTL process design where recycle of the CO₂ and reaction with input H₂ is

used to produce a near-zero emissions of CO₂ without the need for CO₂ sequestration. If a carbon-based source of H₂ is utilized (e.g., steam reforming of methane), then the liquid fuels can be produced at prices that are competitive with petroleum based fuels and the process can have GHG emissions that are reduced with respect to petroleum fuels. If a non-carbon based source of H₂ is utilized (i.e., electrolysis of water), then the emissions from the process will be near-zero, but a low cost of electricity is required to make the liquid fuels cost-competitive.

Höök and Aleklett (2010) has reviewed the CTL technologies and conclude that the feedstock to product conversion ratio prevents CTL from being a global liquid fuel supplier. The ratio from feedstock to product suggests that some CTL scenarios are too optimistic, and although certain countries can pursue this option, CTL cannot be sustained globally. However, it is possible to raise the feedstock to product conversion ratio to allow for a more widespread use of the technology. The near-zero emissions CTL plant designs (Baliban et al., 2010; Elia et al., 2010) are capable of pushing the feedstock to product conversion ratio to levels above 95% if a source of natural gas or cheap electricity can be obtained. The low conversion ratio can also be mitigated by using hybrid energy processes where a combination of feedstocks are input to help increase the conversion ratio and reduce GHG emissions while taking advantage of the low cost of the coal feedstock.

2.1.3. Assessment of state of the art approaches

Coal gasification has existed commercially around the world for almost one hundred years, and has been utilized by the electric power industry for almost four decades. Texaco developed the GEE gasifier from the 1940s and started the first commercial gasification plant in 1983 (Electric Power Research Institute, 1993). Currently, a total of 24 gasifiers have been built in 12 locations for both coal and petroleum coke. The first commercial-scale unit for the electric power industry gasified a total of 1000 dry short tons per day (TPD) of bituminous coal and the largest unit to date is capable of gasifying 2500 dry TPD of coal in a single unit (Electric Power Research Institute, 1993; National Energy Technology Laboratory, 2007b). The ConocoPhillips E-Gas™ gasifier was originally developed by Dow Chemical beginning in 1976. A unit operating in Plaquemine, Louisiana has a capacity of 1400 dry, ash-free TPD for bituminous coal and 1650 dry, ash free TPD for lignite coal and the unit operating at Wabush River, Indiana is able to handle up to 1850 dry, ash-free TPD of high-sulfur bituminous coal. Shell also has a gasifier operating in The Netherlands that has a bituminous coal capacity of 1800 TPD (Electric Power Research Institute, 1993; National Energy Technology Laboratory, 2007b). The operating capacities of these gasifiers would be able to produce approximately 4–5 thousand barrels per day of liquid product, if a feedstock carbon conversion ratio of 33% is assumed (Kreutz et al., 2008). Though the gasifiers described above have been used extensively for electric power generation, a commercial-scale CTL plant has been operating by Sasol at Secunda in South Africa. The project utilized approximately 100 gasifiers to convert over 40 million metric tonnes of coal per year to liquid fuels. The production capacity of 150,000 barrels per day provides 40% of the liquid fuels for South Africa. Sasol operates using two types of FT technology: a low-temperature unit to produce diesel and a high-temperature unit to produce a variety of high-value chemicals (Sasol, 2009). As an alternative to the gasification route, a commercial CTL plant has also been built by the Shenhua Group in China using the direct coal liquefaction (DCL) technology, which liquefies coal at high temperature and pressure over a catalyst with an input of hydrogen, to product transportation fuels. The DCL plant at Erdos, Inner Mongolia started operating in 2009 and when fully operated, is expected to produce 1 megatonnes per year of oil products, or about 25,000 barrel/day (BPD) of fuels (Su & Fletcher, 2010).

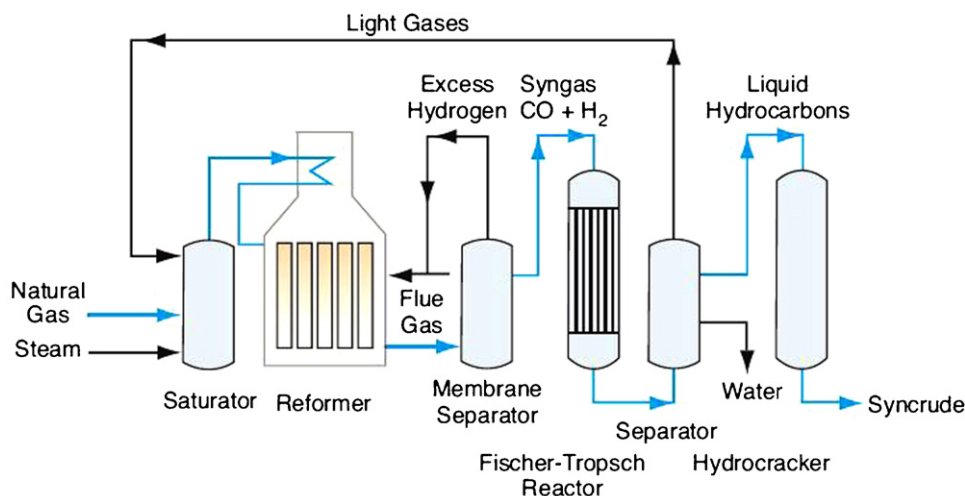


Fig. 2. Gas to liquids process flowsheet (reprinted from Parkinson, 2005).

The cost of CTL plants have been estimated to range from \$1.1 to \$1.6/gallon of gasoline equivalent (GGE) for processes without carbon capture and sequestration (CCS) and from \$1.5 to \$1.8/GGE for processes with CCS (Adams & Barton, 2011a, 2011b; Chen et al., 2011a, 2011b; Cocco et al., 2006; Elia et al., 2010; Erturk, 2011; Jun-ling et al., 2002; Kreutz et al., 2008; Larson et al., 2010; Larson, Fiorese, et al., 2009; Larson & Tingjin, 2003; Li, Gao, et al., 2010; Lin et al., 2010, 2011; Liu et al., 2007, 2009, 2010a, 2010b; Liu, Larson, et al., 2011; Mantripragada & Rubin, 2009, 2011a, 2011b; NAS et al., 2009; Williams et al., 2009; NAS, NAE and NRC, 2009; Vliet et al., 2009; Williams et al., 2011; Zhou et al., 2008, 2009), though the emissions from the processes without CCS can be over twice that of a petroleum refinery while the processes with CCS have emissions that are comparable with petroleum-based processes (Kreutz et al., 2008). The capital investment estimated for a 50,000 BPD CTL plant has been estimated to be around \$100,000/BPD of product for plants that utilize recycle of the unreacted synthesis gas to produce additional liquid product and around \$120,000/BPD for plants with a “once-through” configuration where the unreacted syngas is used for electricity production (Kreutz et al., 2008; NAS, NAE and NRC, 2009). Note that the effects of scaling in the investment cost will be highly dependent on the maximum possible capacity that can be obtained within specific units in the process. Additionally, the overall cost will depend greatly on (i) the cost of coal, (ii) the assumed capital investment and levelized annuity factors, and (iii) the potential to sell any byproduct electricity that the plant will generate.

The amount of carbon in the coal feedstock that is converted to final liquid product ranges from 20% to 35% (Adams & Barton, 2011a, 2011b; Chen et al., 2011a, 2011b; Cocco et al., 2006; Gao et al., 2004; Guang-jian et al., 2010; Han et al., 2009; Kreutz et al., 2008; Larson & Tingjin, 2003; Li, Gao, et al., 2010; Lin et al., 2010, 2011; Liu, Larson, et al., 2011; Mantripragada & Rubin, 2009, 2011a, 2011b; Sudiro & Bertuccio, 2007, 2009; Sudiro et al., 2008; Sun et al., 2010; Williams et al., 2009, 2011; Yu et al., 2010; Zhou et al., 2008, 2009), and is highly dependent on the topology of the process flowsheet used to make the liquid fuels. The “once-through” configurations will generally be on the lower end of that range, due to the conversion of unreacted syngas to CO₂ via combustion/electricity generation. Process configurations with recycle of the CO₂ can achieve higher conversion rates of carbon, though this generally comes at a higher cost of capital for the process. However, the normalized cost of capital (i.e., \$/bpd) will be lower for the processes including syngas recycle. Carbon conversion ratios of near 100% can be achieved if a non-carbon based source of H₂ is input and the reverse water–gas-shift

reaction is used to consume the process CO₂ (Agrawal, Singh, Ribeiro, & Delgass, 2007; Baliban et al., 2010; Elia et al., 2010). In general, the lower-heating value efficiency for a CTL process is in the range of 45–50% (Adams & Barton, 2011a, 2011b; Chen et al., 2011a, 2011b; Kreutz et al., 2008; Li, Gao, et al., 2010; Liu, Larson, et al., 2011; Mantripragada & Rubin, 2009, 2011a, 2011b; Williams et al., 2009, 2011; Yu et al., 2010), and does not vary widely with the choice of either “once-through” or recycle configurations. For processes utilizing CCS, the loss of efficiency is generally 1–2% for the process.

2.2. Gas to liquids (GTL)

2.2.1. Process description

A typical gas to liquids (GTL) process is shown in Fig. 2 (reprinted from Parkinson, 2005) and has a “downstream” series of process units that is very similar to the CTL process. The key difference between these two technologies is the generation of the synthesis gas from the initial feedstock. The natural gas feedstock is generally cleaner than coal feedstocks, and will therefore require a smaller degree of sulfur removal. The natural gas can be converted to syngas either via steam reforming, partial oxidation, or both in sequence (auto-thermal reforming). Though all three of these technologies are commercially mature, oxygen-blown auto-thermal reforming is an attractive option because the process can be tailored to produce the H₂:CO ratio that is needed for FT synthesis. The synthesis gas stream exiting the reactor may be directed to a CO₂ removal unit to recover and sequester the CO₂ prior to entry into the FT units.

2.2.2. Literature review

Out of the three single-feed alternative processes, GTL technology is the most technologically and commercially developed. Overviews of the GTL process can be found in Wilhelm, Simbeck, Karp, and Dickenson (2001) and Basini (2005), and a review of existing GTL technologies can be found in Eliseev (2009).

Iandoli and Kjelstrup (2007) analyzed the thermodynamic efficiency of a GTL system and conducted an exergy analysis for each unit. Hao et al. (2008) simulated GTL process alternatives with iron and cobalt catalyzed FT reactors. Based on several process simulations, including the continuous stirred-tank reactor (CSTR) and plug flow reactor (PFR) reactor configurations, flowsheet structures are determined from the thermal and carbon efficiencies, as well as the product distributions of the process. The cobalt-based system, which did not require CO₂ removal from the FT tail gas, achieved full conversion and is more efficient than the once-through iron-based

system, which includes CO₂ removal from raw syngas. Hall (2005) gave an overview of a technology that involves three reaction steps and two separation steps to produce hydrocarbon liquids.

Kim et al. (2009) simulated a GTL system for maximum fuel production by changing variables such as the temperature of the FT reactor. Arzamendi et al. (2009) performed simulation studies of the integration of steam reforming and combustion of methane in a catalytic microchannel reactor using computational fluid dynamics (CFD). Behroozsarand and Zamaniyan (2011) studied the amine plant in FTS application simulated in HYSYS and MATLAB to optimize the plant's operational parameters. Bao et al. (2010) presented a comprehensive thermo-economic study of a typical GTL system, including the design, simulation, process integration, and economic analysis of the process.

With the generally established process configurations, many studies are dedicated to the improvement of certain segments of a GTL plant on a per unit basis. Heimel and Lowe (2009) compared two configurations for CO₂ capture for a GTL plant: post-combustion CO₂ capture and oxy-fired CO₂ capture. With respect to the reforming segment of the plant, Shigapov and Gesser (1995) reported experimental studies on liquid fuels and hydrogen production from natural gas in a thermal diffusion column (TDC) reactor. Petersen, Christensen, Nielsen, and Dybkjaer (2003) and Bakkerud (2005) discussed the development of the autothermal reactor (ATR) and reforming technologies. Breed et al. (2005) investigated a zone, natural gas reforming reactor in which oxygen or air is first contacted with solid metal bromide. Yagi et al. (2005) demonstrated the performance of catalysts that facilitate CO₂ reforming, and Rabe, Truong, and Vogel (2005) studied low temperature partial oxidation of methane for GTL application.

Dillerop et al. (2010) proposed a novel design of the ATR, namely the reverse flow catalytic membrane reactors for heat integration within the reactor and with the air separation unit (ASU). Agiral et al. (2011) demonstrated a GTL process in a multi-phase flow, non-thermal plasma microreactor based on dielectric barrier discharge. Ha et al. (2010) studied two reforming units, the steam and carbon dioxide reforming of methane to form syngas, and the effect of recycling unreacted syngas mixture to the process efficiency. With recycling, they found that zero emissions from the process can be achieved and a reduction of natural gas used. Lee, Hong, and Moon (2011) performed the simulation and experimental results from the two reforming methods.

A series of papers investigated a novel FTS reactor design with hydrogen permselective membrane. Rahimpour and Elekaei (2009a) outlined a FTS reactor design, modeled mathematically and simulated using MATLAB, in which a fixed-bed reactor is combined with a membrane assisted fluidized-bed reactor to control hydrogen addition. The results showed that the yield in gasoline is higher and CO₂ formation is decreased. Forghani, Elekaei, and Rahimpour (2009) reported that the co-current mode can enhance gasoline production. In Rahimpour and Elekaei (2009b) the reactor was optimized using a Genetic Algorithm (GA) to maximize gasoline blend and minimize CO₂ production. Rahimpour, Forghani, Mostafazadeh, and Shariati (2010) compared the co-current and counter-current modes for the dual-bed FTS reactor, and found that the counter-current produces more gasoline and less unfavorable yields. Rahimpour, Mirvakili, Paymooni, and Moghtaderi (2011) investigated a cascading fluidized-bed membrane reactor (CFMR) configuration for FTS. Rahimpour, Mirvakili, and Paymooni (2011d) showed that a double membrane in the reactor yielded higher gasoline yield. Rahimpour, Khademi, and Bahmanpour (2010) optimized the thermally coupled FTS an dehydrogenation of cyclohexane reactors using the differential evolution (DE) method. In Rahimpour and Bahmanpour (2011), Rahimpour, Mirvakili, and Paymooni (2011b, 2011c), and Rahimpour, Mirvakili, and Paymooni (2011e) the thermally coupled reactors (FTS and

cyclohexane) with hydrogen production are optimized using the DE method.

Methanol and DME production from natural gas have been studied. Steinberg (1998) performed a kinetic study for methanol and hydrogen production, using experimental results from a reactor that produces hydrogen and applying them for methanol synthesis by reacting the hydrogen with CO₂ recovered from coal burning power plant stack gases. Gao et al. (2008) studied a natural gas polygeneration system for methanol and power production and compared the polygeneration system with full-reforming and once through methanol synthesis. The new configuration achieved higher efficiency, determined from an exergy analysis. Pisarenko, Pisarenko, Minigulov, and Abaskuliev (2008) and Pisarenko, Pisarenko, and Sarkisov (2009) developed kinetic models for the steam-CO₂ reforming of methane and the methanol synthesis reactors.

Peng et al. (1999) studied the optimal operation of the DME synthesis step from syngas, in particular the ratio between H₂ and CO in the feed composition. Natural gas and CO₂ reforming were used, as well as combining both reforming technologies with coal gasification to achieve the correct syngas composition. Horstman et al. (2005) studied the feasibility of synthesizing DME from natural gas "on-board" for dual fuel compression ignition (CI) engines to achieve higher thermal efficiency and reduce emissions. Lee et al. (2003) and Cho et al. (2009) optimized the design and operation of a tri-reforming reactor of natural gas for DME synthesis. Bin et al. (2008) studied the polygeneration of DME and electricity, in which syngas enters the DME synthesis step and the residual gas is sent to the power generation unit, and performed an exergy analysis for both the individual product generation and the polygeneration case. Finally, Zhou et al. (2009) combined the syngas from coal gasification and natural gas reforming to achieve the correct C to H ratio for DME synthesis. The coal-only system was also evaluated in this study and compared to the hybrid feedstock process.

Products from the GTL process have been tested for various applications. Lee et al. (2009) presented an economic assessment to determine which product (i.e., FT diesel, DME, or methanol) from the GTL process would be the most profitable under various price scenarios. It was found that FT diesel is the most profitable product out of the GTL process under current natural gas prices, but when natural gas is cheaper, DME is the product of choice. They found that the product selection is more a function of the feedstock prices instead of the product prices. Li, Huang, Wang, and Zhang (2007) examined the particle distribution after fuel combustion, and found that GTL-fuels are cleaner. Other tests, such as combustion characteristics, have been applied to GTL fuel products for diesel engine (Azimov, Kim, Jeong, & Lee, 2011; Jrai et al., 2009; Kim, Beschiero, Jeong, & Lee, 2007; Krahl et al., 2009; Lee, Kim, Ryu, Uhm, & Kim, 2007; Mancarusu, Sequino, & Valieco, 2011; Nguyen, Ishida, & Shioji, 2010, 2011; Ogawa, Ibuki, Minematsu, & Miyamoto, 2007; Wu, Huang, Zhang, & Fang, 2007; Wu, Huang, Zhang, Fang, & Yin, 2007; Xinling & Zhen, 2009), passenger cars (Beatrice, Guido, & Di Iorio, 2010; Lapuerta, Armas, Hernández, & Tsolakis, 2010; Moon, Lee, Choi, & Jeong, 2010), heavy duty engine (Knottenbelt, 2002; Lamprecht, 2007; Soltic, Edenhauer, Thurnheer, Schreiber, & Sankowski, 2009). These tests agree that GTL diesel blends perform similarly to petrodiesel with lower GHG emissions and reduced regulated pollutants (Fernández, Tsolakis, Cracknell, & Clark, 2009).

The implementation of GTL technologies has been and continues to be pursued worldwide. In the United States, the Alaska North Slope is a promising candidate location for a GTL project due to its rich natural gas resources. Ejiofor et al. (2008) performed an economic analysis to transport gas-to-liquids products through the existing Trans-Alaska Pipeline System (TAPS). A comparison between the option of blending GTL products with crude oil (commingled) or as alternate slugs (batching) was completed,

and they determined that batching is the more economic option. Ibrionke et al. (2011) performed a probabilistic economic analysis to transport GTL products as blends with crude oil. For this application, several studies were completed to characterize both the GTL fuels and petroleum to determine the compatibility and flow properties through the pipeline system (Das, Nerella, & Kilkarni, 2007; Ramakrishnan et al., 2003). Other countries with reported studies and demonstration pertaining to GTL fuels include China, in a demonstration program for transit buses (Hao et al., 2010), Bolivia (Udaeta, Burani, Maure, & Oliva, 2007; Velasco et al., 2010), India (Keshav & Basu, 2007), Nigeria (Stanley, 2009), Qatar (Chedid, Kobrosly, & Ghajar, 2007), and Brazil (Branco, Szklo, & Schaeffer, 2010; Szklo et al., 2005).

GTL technologies provide an additional niche in the energy context due to their capability to monetize stranded gases, as well as associated gases that are the by-products from the oil industry, which, in current common practices, are unexploited and flared, respectively. Associated gases are flared because the collection and transportation to the market are uneconomical due to their relatively small amount of production, remote locations, and lack of pipeline infrastructure. The development of smaller scale GTL technologies that can be operated in remote locations, however, can potentially convert these gases into valuable and marketable transportation fuel products, which then can be transported via the oil products pipeline. Suzuki et al. (1996) introduced a technology that converts methane via oxidative coupling of methane (OCM) method for remote natural gas. Olsen and Gobina (2004) discussed the options provided by GTL technologies to monetize stranded gases, and Dong, Wei, Tan, and Zhang (2008) compared Liquefied Natural Gas (LNG) and GTL technologies to exploit these gases. Rahimpour, Ghorbani, Asiaee, and Shariati (2011) assessed a FT reactor, mathematically modeled, for gas flaring application to facilitate additional gasoline product from refineries.

Finally, an optimization-based approach for the natural gas planning problem is proposed in Khalilpour and Karimi (2011). A mixed integer linear programming (MILP) problem is formulated to determine the investment and field development of natural gas for either LNG, Compressed Natural Gas (CNG), or GTL applications, given the fluctuating market demands.

2.2.3. Assessment of state of the art approaches

Natural gas reforming has existed for decades on a commercial scale for the production of hydrogen for petroleum refining and the chemical industries. Of the approximately 41 million tons of hydrogen produced per year, 80% is accomplished using steam reforming of methane (National Research Council, 2004). However, the detailed tubular structure of the steam reforming unit makes it less practical for scale-up. Conversely, the auto-thermal reactor does gain benefits from scale-up and can produce a larger amount of H_2 from the natural gas conversion. Thus, the ATR has been the unit operation of choice in commercial GTL plants (National Research Council, 2004). GTL has been the most commercialized FTL technology due largely in part to the need to utilize stranded natural gas resources throughout the world. Sasol has been operating the ORYX GTL project in Qatar since June 2006 to produce 34,000 barrels/day of diesel, naphtha, and LPG products (Davies, 2003). Since that time, Sasol has looked to both expand the ORYX project to produce up to 100,000 barrels/day of product and develop a new plant in the Escravos region of Nigeria (Sasol, 2006). Recently, Shell has launched the Pearl GTL project in Qatar, which is capable of producing a total of 260,000 barrels/day of oil-equivalent fuels (Shell, 2011).

A major concern with GTL production is the uncertainty behind the capital costs of the plant. Sasol initially reported costs of approximately \$25,000/BPD for the 34,000 BPD ORYX project, but estimates for the expansion of the facility to 100,000 BPD are slated

to be higher (Davies, 2003; Sasol, 2006). In a recent study, the capital cost for an 8,760 BPD GTL plant was estimated to be \$60,020/BPD with the cost scaling to approximately \$44,000/BPD if the plant capacity increased to 34,000 BPD (Liu, Williams, Larson, & Kreutz, 2011c). However, the Shell Pearl GTL project has reported capital costs of \$18–19 billion dollars for their production, or \$74,000/BPD, which may increase to near \$24 billion (Shell, 2011). Though the capital cost estimates contain a large degree of uncertainty, it is only one of two major components that influence the profitability of the process. Specifically, the cost of natural gas will also play a large role in determining the cost of crude oil for which the GTL process can be competitive. In general, the cost associated with producing fuels using the GTL process has ranged from \$40 to \$70 per barrel of crude oil (Bao et al., 2010; Dillerop et al., 2010; Erturk, 2011; Hall, 2005; Heimel & Lowe, 2009; Lee et al., 2009; Liu et al., 2011c; Suzuki et al., 1996; Vliet et al., 2009; Zhou et al., 2009). This estimate is similar to the cost of CTL processes because the cost savings from capital investment in GTL processes is offset by the higher feedstock costs. That is, the capital cost of producing a clean syngas from coal is generally higher due to the high costs of gasification and syngas cleaning compared to auto-thermal reforming of natural gas. However, natural gas costs per unit energy will be higher on average than the corresponding costs for coal.

The carbon conversion ratio in GTL processes is generally much higher than either CTL or BTL processes. The feedstock has a H/C ratio of approximately 4, which allows the resulting synthesis gas to obtain a H_2/CO ratio more appropriate for hydrocarbon formation without the need for additional carbon losses. That is, to obtain the H_2/CO ratio in gasification processes, a water–gas–shift unit is often used which converts some of the CO to CO_2 , and reduces the amount of carbon that can be converted to liquid fuels. Thus, carbon conversion ratios of 65–75% can be readily obtained from processes that recycle unreacted syngas (Bao et al., 2010; Bin et al., 2008; Dillerop et al., 2010; Gao et al., 2008; Ha et al., 2010; Hao et al., 2008; Heimel & Lowe, 2009; Iandoli & Kjelstrup, 2007; Kim et al., 2009; Lee et al., 2009; Liu et al., 2011b, 2011c; Peng et al., 1999; Sudiro & Bertuccio, 2007, 2009; Zhou et al., 2009). Note that “once-through” configurations can be utilized to provide approximately equal energy capacities of electricity and liquid fuels, though the carbon conversion ratio will be reduced to near 40% (Liu et al., 2011c). The lower-heating value efficiency of GTL processes is higher than CTL processes, with ratios of 55–65% being typical (Bao et al., 2010; Dillerop et al., 2010; Gao et al., 2008; Ha et al., 2010; Heimel & Lowe, 2009; Kim et al., 2009; Lee et al., 2009; Liu et al., 2011b, 2011c; Sudiro & Bertuccio, 2009; Zhou et al., 2009). Recycle configurations will have slightly higher efficiencies than “once-through” processes and that the implementation of CCS will penalize the efficiency of a process by about 1–3% (Liu et al., 2011b, 2011c).

2.3. Biomass to liquids (BTL)

2.3.1. Process description

Thermochemical conversion of biomass to liquid fuels (BTL) is shown in Fig. 3 (reprinted from Rudloff, 2007) and follows a very similar pathway to CTL. A gasification train is used to convert the raw biomass feedstock to synthesis gas which must be subsequently cleaned up before being passed to the FT reactors. The key differences with biomass gasification are the high moisture content in as-received biomass and the formation of tars in the gasifier effluent. The moisture level of the biomass should be under a certain threshold (e.g., 20%) for the efficiency of the gasifier to be maintained. Thus, a dryer may be required to pass a hot vapor stream over the biomass to evaporate some of the moisture. Additionally, the tars in the gasifier effluent must also be removed prior to cooling of the syngas to prevent fouling of the syngas cleanup units or the FT reactors. Typically, the gasifier effluent can be passed through

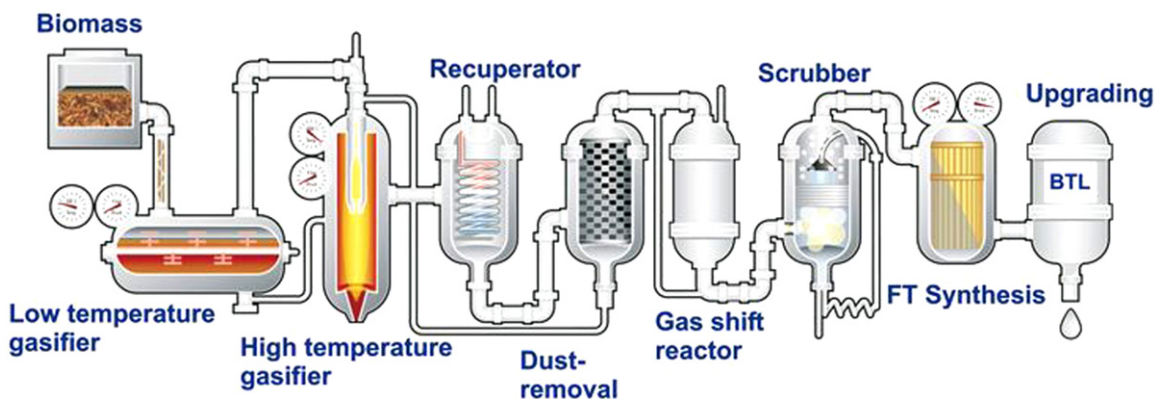


Fig. 3. Biomass to liquids process flowsheet (reprinted from Rudloff, 2007).

a tar cracker to convert the long chain tar molecules to additional syngas.

2.3.2. Literature review—stand alone processes

Numerous studies have investigated various routes of biomass conversion to liquid fuels, as biomass is expected to play a major role in the energy sector in the near future (Lynd et al., 2009; Somerville, Youngs, Taylor, Davis, & Long, 2010). Biofuels are generally categorized as first generation biofuels (e.g., ethanol from cellulosic biomass) and second generation biofuels, which include thermochemical conversion of biomass. Thermochemical conversions also have several alternatives, including pyrolysis, gasification, hydrothermal, direct combustion, liquefaction, supercritical water extraction, and air-steam gasification.

Several reviews exist. Zhang (2010) reviewed technologies for second generation bio-automotive fuels from forest residues. Sunde et al. (2011) reviewed the environmental impacts and costs of hydrotreated vegetable oils, transesterified lipids and woody BTL. Balat, Balat, Kirtay, and Balat (2009a) reviewed pyrolysis systems that yield charcoal, bio-oil, and fuel gas, and discuss gasification systems and their potential products that can be generated from syngas in the second part of the review (Balat, Balat, Kirtay, & Balat, 2009b). Demirbas (2007) reviewed methanol synthesis and FT synthesis from biomass syngas. Naik, Goud, Rout, and Dalai (2010) reviewed the production of first and second generation biofuels. First generation biofuels appear unsustainable due to limited feedstock availability and competition with the food market. Thus, a focus on second generation lignocellulosic biofuels is increasing. Laser, Larson, et al. (2009) evaluated 14 routes of mature biomass refining scenarios and calculated the efficiency, environmental impact, and economic performance of each route. Damartzis and Zabaniotou (2011) reviewed the thermochemical conversion to second generation biofuels through an integrated process design. Bulushev and Ross (2011) reviewed the conversion of biomass via pyrolysis and gasification. Bridgwater and Double (1991) reviewed the production costs of liquid fuels from biomass via various routes using a techno-economic simulation.

Tijmensen et al. (2002) explored FT liquid and power production from biomass, postulated that the process can be competitive, and discussed the potential of economic and technological improvements. Hamelinck et al. (2004) performed a simulation on FT production from biomass and suggested that the process will only be profitable when oil price increases and/or environmental benefits of cleaner FT diesel are valued. Henrich et al. (2009) determined that large BTL plant is more profitable than small ones through cost estimates for biosynfuel production. Larson, Jin, et al. (2009) analyzed a large-scale gasification system that produces electricity, diesel, gasoline, DME, or hydrogen from switchgrass. Five processes

were evaluated, and they found that the once-through systems have high electricity output, which are favorable when the electricity price is high.

Seiler et al. (2010) discussed a design concept of an enhanced BTL process that includes an external energy input to increase fuel production. Tock et al. (2010) performed thermodynamic and economic analysis of an integrated process that produces FT fuels, methanol, and DME. Sarkar et al. (2011) compared the production of fuels and chemicals (i.e., methanol, DME, FT fuels, and ammonia) from two types of biomass gasifiers. Sues et al. (2010) conducted exergy analyses on 5 biowastes to fuels routes via gasification (i.e., biomass to SNG, methanol, FT fuels, hydrogen, heat and electricity). Swanson et al. (2010) compared the costs of two BTL plants based on corn stover gasification. Manganaro et al. (2011) completed an energy analysis of residual biomass to fuels with a spreadsheet method. Perales et al. (2011) developed a technoeconomic assessment of ethanol production via thermochemical and catalytic conversion. They found that the capital cost for the thermochemical route is higher than the biochemical route, but the biochemical route has larger operating cost.

Williams et al. (1995) investigated the co-production of methanol and hydrogen from gasified biomass for low-emission fuel applications. Hamelinck and Faaij (2002) evaluated the different technologies associated with methanol and hydrogen production using simulation and analyzed for their economic and energy performances, showing that methanol and hydrogen are viable fuel alternatives for the future. Demirbas (2008) provided an overview of biomethanol production from waste. Kumabe et al. (2008) studied the conversion of woody biomass to methanol. Li et al. (2008) analyzed the performance of a polygeneration system for methanol and electricity. Zwart and Boerrigter (2005) investigated the feasibility and economic performance of co-producing SNG with FT fuels. Compared to the liquids-only process, the polygeneration systems shows that synergy can reduce energy consumption.

Mignard and Pritchard (2008) explored the enhancement of biomass syngas with hydrogen input from electrolysis for methanol production. Zhang, Xiao, et al. (2009) simulated a methanol production process from biomass in interconnected fluidized beds. Amigun et al. (2010) evaluated the potential of biomethanol production from non-woody plant gasification in South Africa. Economic analysis suggested the right plant scale, taking the biomass availability and supply chain into account. Larger plants will achieve economies of scale, but will require more biomass input, increasing the transportation cost.

Clausen, Houbak, et al. (2010) analyzed a catalytic methanol production from biomass gasification, electrolysis of water, CO₂ from post-combustion capture and autothermal reforming of natural gas or biogas. Six plant configurations were compared and the

lowest cost was achieved by the plant with electrolysis of water, gasification of biomass, and autothermal reforming of natural gas. Van Rens et al. (2011) performed an exergy analysis for a BTL plant producing methanol, DME, or hydrogen. Renó et al. (2011) studied the methanol production from sugarcane bagasse. Ng and Sadhukhan (2011) studied the economics of integrating a bio-oil platform for producing methanol and combined heat and power. A thermo-economic study on thermochemical ethanol production is presented in He and Zhang (2011). Ethanol is produced via gasification, alcohol synthesis and alcohol separation. The study showed that the capital cost of this process is high, and not able to compete with the biochemical route of ethanol production.

Ahlgren et al. (2008) studied the conversion of farm-grown biomass to FT diesel and DME. Chohfi (2008) discussed the potential of DME in the sugarcane value chain. Ju et al. (2009) simulated a conceptual design of biomass to DME and their results suggested that better environmental performance is achieved compared to biomass combustion. Zhang, Solli, et al. (2009) performed exergy analysis for the biomass steam gasification to DME process.

Li et al. (2009), Li, Wang, et al. (2010) reported a pilot scale demonstration of corncob-derived syngas conversion to DME. Clausen, Elmegaard, et al. (2010) modeled and simulated two DME plants, including the once through and recycle configurations of the catalytic conversion of syngas from torrefied woody biomass. Kim et al. (2010) developed a MINLP to synthesize a DME and electricity production process from biomass. The superstructure also includes natural gas and coal as feedstock options, but only biomass is selected in the case study. Chang et al. (2012) developed experimental and kinetic simulation of biomass to DME.

Several studies investigated ethanol production via thermochemical routes. De Kam et al. (2009) studied a biomass integrated gasification combined cycle (BIGCC) system to incorporate heat and power production in dry-grind ethanol facilities. Kou and Zhao (2011) evaluated the environmental and economic performance of a thermochemical ethanol production process under extreme weather conditions. Cherubini and Jungmeier (2010) developed a process that produces ethanol, electricity, heat, and chemicals and Hess, Wright, and Kenney (2007) highlighted the logistics of using cellulosic biomass feedstocks for ethanol production.

Brown (2007) and Agrawal, Singh, Ribeiro, Delgass, and Perkins (2009) proposed a hybrid thermochemical/biological process that combines syngas production and fermentation to produce biofuels. Cucek et al. (2011) developed an integrated dry-grind ethanol system with fermentation or catalytic mixed alcohol synthesis using corn stover as feedstock.

In addition to a single BTL process, all biomass conversion routes, including thermochemical, catalytic, and biochemical, can be integrated into the biorefineries concept. The idea of an integrated biorefinery concept is that multiple types of biomass feedstocks can be converted into various biofuels and biochemicals, allowing a flexible approach to allocate the products depending on the constraints of the system (Cherubini, 2010a; Demirbas, 2010; Sammons, Eden, Yuan, Cullinan, & Aksoy, 2007). Centi, Lanzafame, and Perathoner (2011) gave an overview of a second generation biofuels biorefinery and the socio-political impact it will have. Cherubini et al. (2009) combined first and second generation biofuels in his discussion. Kokossis and Yang (2010) highlighted that the process systems engineering approach plays a key role in the development of efficient biorefineries.

Chew and Bhatia (2008) discussed a catalytic technology biorefinery based on palm oil, which includes biomass gasification and FTS in its technology portfolio. Sammons et al. (2008) used a process systems approach and combined process and economic modeling for optimal biorefinery product allocation. Laser, Jin, et al. (2009) developed seven process designs co-producing ethanol, FT fuels, hydrogen, methane, and power, and three processes

co-producing animal feed protein from switchgrass. Dale et al. (2009) investigated the possibility of producing protein feeds with fuels and chemicals from biomass. Pinatti et al. (2010) discussed a biorefinery concept with eleven thermochemical routes and one biological route. Bao et al. (2011) used a short-cut method and optimization-based approaches to synthesize and screen the technological pathways and inefficient distribution flows over the network. Sharma et al. (2011) used a MILP financial planning model for a multi-product, multi-platform biorefinery. Tay et al. (2011) synthesized a sustainable biorefinery with maximum economic performance and minimal environmental impact via a fuzzy mathematical programming model to account for the conflicting nature of the two main objectives.

2.3.3. Literature review—supply chain networks

Unlike coal or natural gas, which are produced in a large-scale, centralized manner, biomass production is more distributed and its supply chain involves more logistical issues (Rentizelas, Tolis, & Tatsiopoulou, 2009). Thus, an optimal allocation of biomass resources with minimum transportation cost is a crucial aspect of BTL technologies and studies on biomass supply chain exist in the literature. A review on biomass supply chain studies can be found in Gold and Seuring (2011), taking into consideration the collection, storage, and distribution of biomass. An, Wilhelm, and Searcy (2011a) reviewed the literature on biofuel supply chain research, classified in decision time frame and level in the supply chain (i.e., upstream, midstream, or downstream). Iakovou, Karagiannidis, Vlachos, Toka, and Malamakis (2010) reviewed the features of waste biomass supply chains and the potential conversion technologies for heat and power production.

Ravula et al. (2008) developed a biomass transportation system based on cotton logistics and simulated using a discrete event simulation procedure. Uslu, Faaij, and Bergman (2008) evaluated the role of pretreatment technologies, such as torrefaction, pelletization, and pyrolysis, on bioenergy chains, particularly in increasing the energy density of transported materials. Cundiff, Fike, Parrish, and Alwang (2009) discussed the logistics constraints in developing bioenergy systems in the southeastern region of the United States. Yu, Bartle, Li, and Wu (2009) developed a discrete mathematical model for mallee biomass production and transportation logistics in Western Australia. transportation logistics. Meehan and McDonnell (2010) analyzed biomass availability and delivery for the University College Dublin under minimum land use impact, maximum energy scenario, and minimum environmental impact. van Dyken et al. (2010) developed a MILP approach for the biomass supply chain, highlighting the change in biomass moisture and energy content during storage for long-term processing. Huang et al. (2010) formulated a multi-period optimization model for the biofuels supply chain.

The facility location problem is investigated for BTL plants. Parker et al. (2010) performed resource assessment and biorefinery facility location optimization for the western region of the United States. Dal-Mas et al. (2011) studied strategic planning and investment capacity planning under price uncertainty for ethanol supply chain, whose framework can be applied to other systems. Leduc et al. (2008) developed a MILP problem to solve the methanol facility location problem for a case study in Austria, taking the biomass supply chain into account. Leduc et al. (2009) considered a transportation model to estimate the logistic demands of biomass supply to the plant and the supply to the gas station for methanol product from wood gasification. Cost analysis, plant location and efficiency, wood cost, and operating hours are among the most influential factors in the fuel production cost. Leduc, Lundgren, et al. (2010) considered locations of methanol production plants for northern Sweden with demand scenarios up to 2025. Kim, Realff, Lee, Whittaker, et al. (2011) developed a mixed integer optimization

model for the biomass supply chain network for the Southeastern region of the United States. The system consists of two conversion plants, the first one being a pyrolysis plant that produces biooil, char, and fuel gas, and a second gasification-based plant that produces gasoline and biodiesel. The work is extended in Kim, Realf, and Lee (2011) to consider uncertainty in a two stage mixed integer stochastic program, and the robustness of the solution is analyzed using Monte Carlo simulation.

Aksoy et al. (2008) determined the biorefinery locations based on poultry litter in Alabama so as to minimize transportation cost. Tittmann, Parker, Hart, and Jenkins (2010) developed a mixed integer linear, biorefinery citing model that determines the location, size, and type of the biorefinery using geographic information system (GIS) technology for the spatial configurations in the state of California. Bai et al. (2011) studied biorefinery location and supply chain planning under traffic congestion, minimizing transportation cost. Bowling et al. (2011) developed a facility location and supply chain optimization for biorefineries, taking into account the sales and costs of feedstocks, transportation cost, capital cost, and operational cost. Giarola et al. (2011) studied the strategic design and planning of corn grain and stover-based bioethanol supply chains via first and second generation technologies. A multi-period, multi-echelon, spatially explicit MILP model is developed to optimize the environmental and financial performance simultaneously.

Additionally, similar methods have been applied for non-thermochemical conversion facilities. Ayoub, Martins, Wang, Seki, and Naka (2007) studied a two-level bioenergy decision system planning problem. Dunnett et al. (2008) studied a lignocellulosic bioethanol supply chain with pretreatment. Eksioglu et al. (2009, 2010) studied the design of a biomass supply chain system for ethanol production from corn stover and woody biomass. Zamboni, Bezzo, and Shah (2009), Zamboni, Shah, et al. (2009) investigated a spatially explicit approach formulated as a MILP to minimize cost and environmental impacts for corn based ethanol networks (Zamboni, Shah, et al., 2009) and formulated a multi-objective environmental optimization (Zamboni, Bezzo, et al., 2009). Marvin et al. (2012) studied a biochemical-based cellulosic biomass-to-ethanol supply chain for the Midwestern United States by solving a MILP problem. The conversion technology used to convert agricultural residues is dilute acid pretreatment and enzymatic hydrolysis.

Leduc, Starfelt, et al. (2010) addressed the optimal locations for lignocellulosic ethanol facilities with combined heat and power production. Cucek et al. (2010) developed a MILP approach for regional renewable energy supply chains, taking into account a four-layer superstructure, starting from harvesting, preparation, processing to the distribution of products. Hacatoglu et al. (2011) performed a feasibility study on bioenergy system for the Great Lakes based on lignocellulosic biomass with minimal adverse impacts on food and fiber production. Akgul et al. (2011) developed a MILP model for the optimal design of a corn-based bioethanol supply chain to minimize its total cost, applied to Northern Italy region. The mathematical model incorporated a neighborhood flow representation, which governed the delivery route of materials. An et al. (2011b) evaluated a lignocellulosic biofuel and petroleum-based fuel supply chain for Central Texas. Gan and Smith (2011) developed a generic framework for the supply of biomass to conversion facilities that produce electricity and cellulosic ethanol. Kocoloski et al. (2011) discussed the impact of cellulosic ethanol refineries location and size on the price of product ethanol. The problem was formulated as a MIP with an economic objective function.

Rentizelas, Tatsiopoulou, et al. (2009) and Rentizelas and Tatsiopoulou (2010) studied a hybrid optimization method to solve an optimal location problem for bioenergy (i.e., heat and power) generation facilities. Charlton, Elias, Fish, Fowler, and Gallagher (2009) evaluated the potential of biomass energy systems in Wales. Marti and Gonzalez (2010) combined GIS spatial studies

with linear optimisation for the design of a bioenergy chain. Panichelli and Gnansounou (2008) used a GIS-based decision support system to allocate forest wood residues to torrefaction plants for a gasification unit in a power plant. Zhang et al. (2011) combined GIS-based method to identify feasible locations for forest biomass to fuel facilities with transportation cost model.

Biomass supply chain networks can also be incorporated into a larger scale, regional, renewable energy planning. Several methodologies exist, such as the SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, expert opinion “Delphi” methods, and the MARKAL model (Borjesson & Ahlgren, 2010; Clarke, Jablonski, Moran, Anandarajah, & Taylor, 2009; Gul, Kypreos, Turton, & Barreto, 2009; Jablonski, Strachan, Brand, & Bauen, 2010; Terrados et al., 2009). These models, which are not reviewed in this paper, incorporate the multiple decision analysis techniques for multiple time horizons, as well as competing objectives that may exist within a region, to assist decisions on regional energy policies.

The environmental benefits of biomass-based processes are investigated via life cycle analysis studies. Wahlund et al. (2004) compared the life cycle analysis for different processes, including biomass pelletization for electricity production and fuels production (i.e., methanol, DME, ethanol). Wu et al. (2006) analyzed the GHG emissions for different fuels, including FT diesel and DME from switchgrass. Larson (2006) reviewed studies on LCA for different biomass to liquids systems, including first and second generation biofuels. Xiao et al. (2009) studied the performance of biomethanol production from rice straw in China. Dowaki and Genchi (2009) studied the LCA of DME and methanol production via the BLUE tower process. Monte carlo simulation is used to account for the uncertainties in the biomass preprocessing, moisture content, and transportation distance. Hoefnagels et al. (2010) presented a comprehensive LCA calculation for biofuel systems. Cherubini (2010b) calculated GHG balances for a bioenergy system that produces electricity, heat, and biofuels. Joelsson and Gustavsson (2010) compared the emissions and oil use for the polygeneration system of FT fuels, methanol, and DME. Higo and Dowaki (2010) investigated the LCA for DME production from various biomass species in Japan and Papua New Guinea.

2.3.4. Assessment of state of the art approaches

Biomass to liquids is not nearly as commercially developed as CTL or GTL, though a large amount of small facilities are currently under construction. For instance, Choren has developed a beta facility that produces 18 million liters of diesel per year (310 BPD) using an estimated capital cost of 50 million euro (160,965 euro/BPD), and plans to develop a 200 million liter plant (3450 BPD) in the coming years (Rudloff, 2007). Udhe is organizing the BioTFuel project to spend 113 million euro over the next seven years to produce BTL fuels (Heinritz-Adrian, 2010). In India, Bioleum Resources is looking to convert multiple biomass feedstocks to liquid fuels. In the United States, BTL plants have been estimated to cost approximately \$150,000/BPD due largely to the small scale that the plants are assumed to be operated (near 5000 BPD) (Kreutz et al., 2008).

The overall cost for a BTL plant is strongly dependent on the estimated capacity of the plant. Note that the following conclusions apply to the references under the BTL category in Table 2. Due to assumed restrictions in feedstock flow rate, small plant capacities of 10,000 barrels/day and lower have been thoroughly investigated in the literature. The break-even oil prices for these processes are in the range of \$100–150 per barrel of oil, and are highly dependent on the type and price of biomass used in the study. A typical process flowsheet for a BTL refinery is very similar to a CTL flowsheet, and will have high costs of capital for syngas generation and cleaning, oxygen production, and the FT reactors. This implies that the overall capital costs for a BTL process may only be slightly higher than a

CTL process if biomass gasification can be proved commercially on a large scale and the necessary supplies of biomass feedstock are readily available. The other major component of the overall cost of a BTL process will be the purchase price of the biomass feedstock, which will have a higher cost per unit energy than coal feedstocks. Note that the economics of a BTL process are strongly effected if a cost is associated with any CO₂ that is avoided. Due to the carbon storage in the biomass, BTL processes will have a GHG lifecycle that has a near-zero net emissions. Typical petroleum-based processes will emit 0.5 tons of CO₂ per barrel of product (Kreutz et al., 2008), so a tax on life-cycle GHG emissions could raise the cost of liquid fuels production from petroleum to levels that would make BTL processes more competitive.

The carbon in the biomass that is converted to the liquid fuels is very similar to coal processes, with a range of 25–35% being typical. Note that carbon conversion ratios of near 100% can be achieved if a non-carbon based source of H₂ is input and the reverse water–gas-shift reaction is used to consume the process CO₂ (Agrawal et al., 2007; Baliban et al., 2010; Elia et al., 2010). Though the biomass will have a higher H/C ratio than the coal feedstocks, the oxygen present in the biomass will hinder liquid fuels production because it will either leave the process as H₂O or CO₂. “Once-through” processes can be utilized for electricity generation, though the fraction of carbon converted will be lower. The lower-heating value efficiency of BTL processes is also very similar to the CTL figures, with a range of about 45–55%. The exact value will be dependent on whether a “once-through” or recycle configuration is used or whether CCS is implemented.

3. Hybrid feedstock energy processes

The development of the three single feedstock energy processes opens up opportunities to develop hybrid energy processes. Hybrid energy processes provide a compelling alternative in the portfolio of energy resource production, due to their flexibility in converting multiple types of feedstock inputs into a consistent range of products. Moreover, hybrid energy systems can have synergistic effects due to the combined advantages of each individual system. For example, combining coal or natural gas with biomass as feedstocks can reduce the cost of fuel production compared to a pure BTL process. On the other hand, using biomass as a feedstock can reduce the GHG emissions compared to either a coal and natural gas-based process. In the supply chain analyses, combining coal, natural gas, and biomass feedstocks will have an effect in the facility locations of hybrid energy facilities and trade offs between the centralized production of coal and natural gas and the distributed production of biomass can be investigated.

Table 4 summarizes the contributions for hybrid feedstock energy processes, namely the coal and natural gas to liquids (CGTL), coal and biomass to liquids (CBTL), natural gas and biomass to liquids (BGTL), and coal, biomass, and natural gas to liquids (CBGTL) processes, based on a classification in (a) stand-alone processes, and (b) energy supply chain system. Further classifications of the contributions of each publication follow the description outlined in Section 2. Table 5 organizes the contributions listed in Table 4 based on the products of the energy processes. The five main liquid products from the thermochemically based, indirect liquefaction of the feedstocks are gasoline, diesel, kerosene, methanol, and dimethyl ether (DME). Other products listed on the table (i.e., electricity, hydrogen, LPG, etc.) are co-products of the reviewed processes.

3.1. Coal and natural gas to liquids (CGTL)

The integration of the CTL and GTL conceptual designs can be manifested in several different configurations. Cao et al. (2008)

combined CTL and GTL by injecting methane to the gasification reactor and reported a synergistic effect in producing syngas with H₂:CO ratio close to 2, which is the stoichiometric requirement of the FT process. Sudiro and Bertuccio (2007) coupled steam-reforming of natural gas and steam-gasification of coal in a reactor that uses solar energy as heat source. They found that the thermal efficiency of the hybrid process is higher than the coal-only or natural gas-only systems. In another process, Sudiro and Bertuccio (2009) used separate gasification and reforming processes with CO₂ recycle to the gas reforming block and observed reduction in CO₂ emission from the CTL case. The hybrid energy system's emissions and economic performances are in between the CTL and GTL systems.

Studies that performed exergy analysis over hybrid CGTL systems include Zhou et al. (2008) and Li et al. (2011). Zhou et al. (2008) investigated the co-feeding of coal and natural gas to co-produce DME as fuel replacement and electricity. Higher exergy efficiency is obtained by the hybrid feeding and co-production of products. Li et al. (2011) conducted an exergoeconomic of a polygeneration system with coal and coke oven gas, producing methanol, dimethyl ether, and dimethyl carbonate.

Zhou et al. (2009) combined the syngas from coal gasification and natural gas reforming to achieve the correct C to H ratio for DME synthesis, eliminating the need for a water gas shift reactor to shift the syngas composition. The hybrid process is compared with the coal-only and natural gas-only systems in terms of economic performance, energy efficiency, and environmental impact. Similarly, one of the case studies in Peng et al. (1999), reviewed in Section 2.2, involved the combination of natural gas reforming technology with coal gasification to achieve the correct H₂ to CO ratio in the feed composition.

Adams and Barton (2011a) performed a techno-economic analysis of a system that converts coal and natural gas to electricity, methanol, and FT fuels under various carbon policies and market conditions. They proposed a strategy where natural gas reforming is used to cool the gasifier, showing increased energy efficiency for the overall process. In Adams and Barton (2011b) the work is extended to incorporate solid oxide fuel cells as the primary electricity generator. They found that it is most beneficial when the fuel cells are used in conjunction with carbon capture and sequestration (CCS).

3.2. Coal and biomass to liquids (CBTL)

3.2.1. Single stand-alone processes

Increasing attention is given to hybrid coal and biomass energy systems, since biomass incorporation can reduce the life cycle emissions compared to coal-only systems. Warren and El-Halwagi (1996) proposed two configurations for a co-generation system that produces FT liquid fuel and hydrogen from coal and municipal solid waste, including cellulosic and plastic wastes. The two configurations vary in the production route of hydrogen, which is either produced from coal or from cellulosic waste. Chmielniak and Sciazko (2003) suggested co-gasification of biomass and coal for methanol synthesis.

In Kreutz et al. (2008), the combined coal and biomass (CBTL) process is highlighted out of the 16 configurations of CTL, BTL, and CBTL processes because of its potential to have net zero GHG emission to the atmosphere (i.e., when the release of CO₂ to the atmosphere is equal to CO₂ in-take during photosynthesis). They found that the “once-through” configuration for the polygeneration plant, where residual syngas from the FT synthesis is sent to a power generating unit, is more profitable than the “recycle” plant configuration, where the residual syngas is recycled for additional fuel production. Based on this report, Williams et al. (2009) emphasized the benefits of the polygeneration of liquid fuels and

Table 4
Hybrid energy systems contributions on stand-alone processes and energy supply chain networks. The numerical figures refer to the reference list at the end of this paper.

Component	CGTL	CBTL	BGTL	CBGTL
<i>Stand-alone systems</i>				
Conceptual design	Li, Liu, He, Wang, and Pistikopoulos (2011), Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Zhou et al. (2009), Peng et al. (1999)	Larson et al. (2010), Chen et al. (2011b), Chen et al. (2011a), Warren and El-Halwagi (1996), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b), Borgwardt (1997), Li, Hong, Jin, and Cai (2010), Dong and Steinberg (1997)	Baliban et al. (2010), Baliban, Elia, and Floudas (2011), Baliban, Elia, and Floudas (2012)
Process simulation	Li et al. (2011), Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Zhou et al. (2009), Peng et al. (1999)	Larson et al. (2010), Chen et al. (2011b), Chen et al. (2011a), Warren and El-Halwagi (1996), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b), Borgwardt (1997), Li, Hong, et al. (2010), Dong and Steinberg (1997)	Baliban et al. (2010)
Economic analysis	Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Zhou et al. (2009)	Larson et al. (2010), Chen et al. (2011b), Chen et al. (2011a), Liu, Whitaker, Pistikopoulos, and Li (2011), Warren and El-Halwagi (1996), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b), Borgwardt (1997), Dong and Steinberg (1997)	Baliban et al. (2010), Baliban et al. (2011), Baliban et al. (2012)
Heat integration	Sudiro and Bertuccio (2009), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2009)	Larson et al. (2010), Chen et al. (2011b), Chen et al. (2011a), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b), Dong and Steinberg (1997)	Elia, Baliban, and Floudas (2010), Baliban et al. (2011), Baliban et al. (2012)
Power integration	Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2009)	Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b), Li, Hong, et al. (2010)	Elia et al. (2010), Baliban et al. (2011), Baliban et al. (2012)
Water integration				Baliban et al. (2012)
Process synthesis		Chen et al. (2011b), Chen et al. (2011a)		Baliban et al. (2011), Baliban et al. (2012)
Life cycle analysis		Larson et al. (2010), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b)	Elia, Baliban, Xiao, and Floudas (2011), Baliban et al. (2012)
Sensitivity analysis	Sudiro and Bertuccio (2007), Zhou et al. (2009), Peng et al. (1999), Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Liu, Whitaker, et al. (2011)	Kreutz et al. (2008), Liu et al. (2011b), Williams et al. (2011), Chen et al. (2011b), Chen et al. (2011a), Larson et al. (2010)	Liu et al. (2011b), Li, Hong, et al. (2010)	Baliban et al. (2010), Baliban et al. (2011), Baliban et al. (2012), Elia et al. (2011)
<i>Uncertainty</i>				
<i>Network-based analyses</i>				
Supply chain		Liu, Whitaker, et al. (2011)		Elia et al. (2011)

electricity from coal and biomass with carbon capture and storage. In addition to reduced GHG emissions from biomass, the CCS system can potentially result in a net-negative emission for the plant. The work of Kreutz et al. (2008) is followed up in a recent paper (Liu, Larson, et al., 2011) that highlights the economic advantage of the polygeneration system. Additionally, their results suggest that low-emitting synfuels produced by the hybrid system would be more profitable than the production of cellulosic ethanol and would require half as much lignocellulosic biomass.

Larson et al. (2010) and Larson, Fiorese, et al. (2009) studied systems that produce liquid fuels and electricity from coal and biomass with CCS for an Illinois case study. Using the once-through CBTL-CCS conceptual design developed in Kreutz et al. (2008) and taking a mixture of switchgrass and mixed prairie grass as biomass inputs, several case studies were completed and compared with their CTL and BTL counterparts. Life cycle analysis and economic

analysis were completed, and the CBTL system was able to compete economically with the CTL and BTL systems with zero emissions. The CBTL system balances the economic and environmental performances, serving as the middle ground in the trade-off between fuel prices and environmental impact. While the CTL system is able to generate fuels at lower costs, its emission values are high. On the contrary, the BTL system has net-negative emissions, but the fuel cost is high due to higher feedstock prices. Williams et al. (2011) suggested that the CBTL-CCS polygeneration system is an attractive alternative to decarbonize coal power plants.

Chen et al. (2011b) developed an energy polygeneration system that uses coal and biomass to produce power, liquid fuels, and chemicals, whose performances were studied in detail under different scenarios of market prices. The optimal design is determined by solving a MINLP problem under different feedstock and product prices, and potential carbon policy scenarios. To address the

Table 5

Hybrid energy process systems organized by product type.

Products	CGTL	CBTL	BGTL	CBGTL
Gasoline	Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Adams and Barton (2011a), Adams and Barton (2011b)	Williams et al. (2009), Larson et al. (2010), Larson, Fiorese, et al. (2009), Chen et al. (2011b), Chen et al. (2011a), Warren and El-Halwagi (1996), Liu, Whitaker, et al. (2011), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b)	Baliban et al. (2010), Elia et al. (2010), Baliban et al. (2011), Baliban et al. (2012), Elia et al. (2011)
Diesel	Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009), Adams and Barton (2011a), Adams and Barton (2011b)	Williams et al. (2009), Larson et al. (2010), Larson, Fiorese, et al. (2009), Chen et al. (2011b), Chen et al. (2011a), Warren and El-Halwagi (1996), Liu, Whitaker, et al. (2011), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011)	Liu et al. (2011b)	Baliban et al. (2010), Elia et al. (2010), Baliban et al. (2011), Baliban et al. (2012), Elia et al. (2011)
Kerosene		Warren and El-Halwagi (1996), Liu, Larson, et al. (2011), Kreutz et al. (2008), Folkedahl, Snyder, Stregge, and Bjorgaard (2011)		Baliban et al. (2010), Elia et al. (2010), Baliban et al. (2011), Baliban et al. (2012), Elia et al. (2011)
Methanol	Li et al. (2011), Adams and Barton (2011a), Adams and Barton (2011b)	Chen et al. (2011b), Chen et al. (2011a), Chmielniak and Sciazko (2003)	Borgwardt (1997), Li, Hong, et al. (2010), Dong and Steinberg (1997), Clausen, Houbak, et al. (2010)	
Dimethyl ether	Li et al. (2011), Zhou et al. (2008), Zhou et al. (2009), Peng et al. (1999)			
Dimethyl carbonate ^a	Li et al. (2011)			
LPG ^a	Sudiro and Bertuccio (2007), Sudiro and Bertuccio (2009)			
Electricity ^a	Adams and Barton (2011a), Adams and Barton (2011b), Zhou et al. (2008), Zhou et al. (2009)	Williams et al. (2009), Larson et al. (2010), Larson, Fiorese, et al. (2009), Chen et al. (2011b), Chen et al. (2011a), Liu, Whitaker, et al. (2011), Liu, Larson, et al. (2011), Kreutz et al. (2008), Williams et al. (2011), Chmielniak and Sciazko (2003)	Liu et al. (2011b), Li, Hong, et al. (2010)	Baliban et al. (2011), Baliban et al. (2012), Elia et al. (2011)
Hydrogen ^a		Warren and El-Halwagi (1996)		

^a Dimethyl carbonate, LPG (liquefied petroleum gas), electricity, and hydrogen are byproducts of the processes in the cited literatures and are not reviewed in this paper.

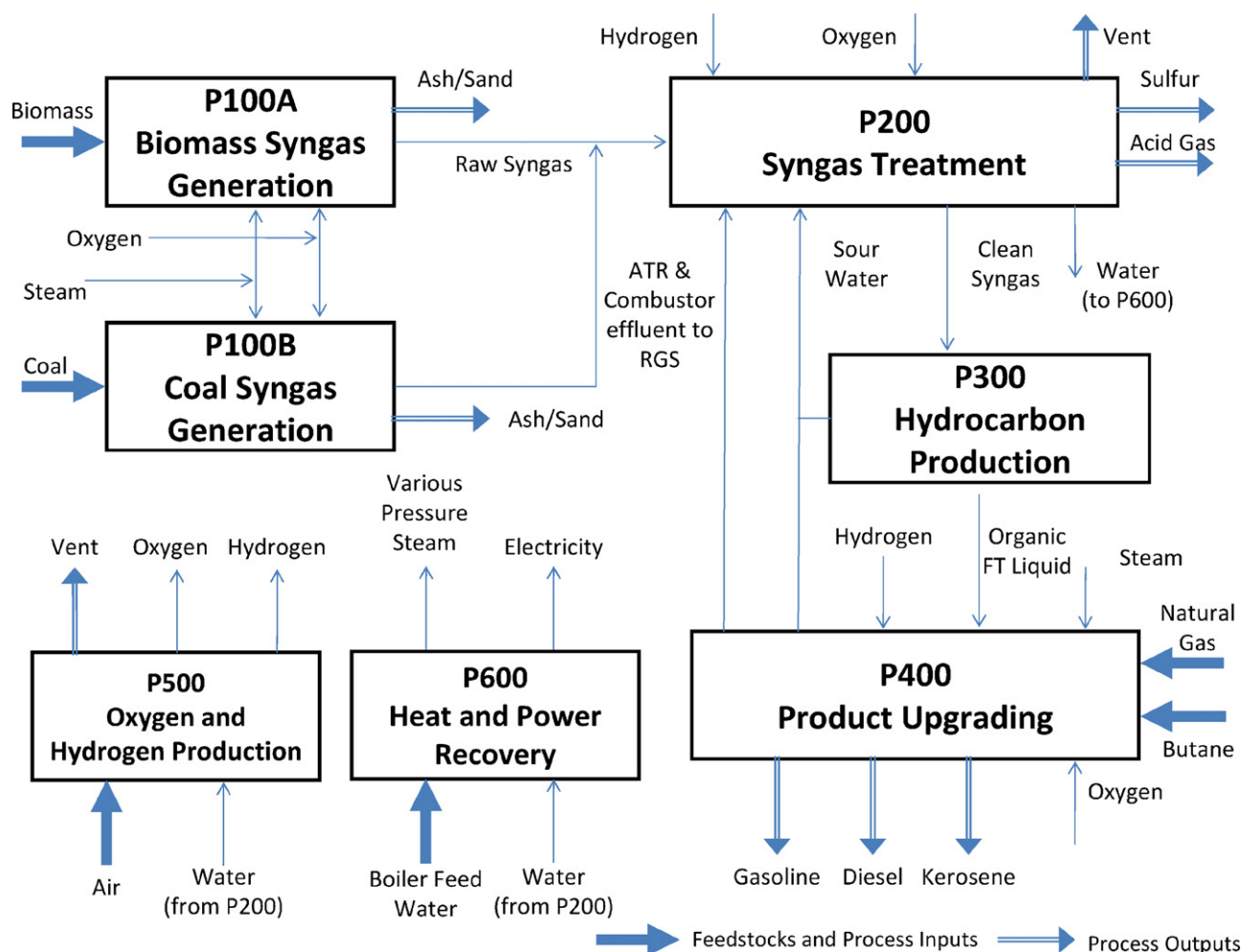


Fig. 4. Coal, biomass, and natural gas to liquids process flowsheet (reprinted from Baliban, Elia, & Floudas, 2010).

changes in prices and fluctuations throughout the plant lifetime, the study is extended to a flexible polygeneration system in Chen et al. (2011a). Design and operational decisions are obtained by solving a two-stage programming problem, and it is found that the flexible polygeneration systems generate higher net present values than their static counterparts.

Experimental works that demonstrate the viability of the CBTL process have also been pursued. Ahmaruzzaman and Sharma (2008) reported experimental results of liquid fuels derived from petroleum vacuum residues, coal, and biomass. Folkedahl et al. (2011) developed and demonstrated the CBTL technology with an iron-based FT catalyst, whose products are upgraded to synthetic isoparaaffinic kerosene that closely meets the specifications of military-grade jet fuel.

3.2.2. Supply chain networks

An energy supply chain network consideration for CBTL systems is studied in Liu, Whitaker, et al. (2011), where the optimal locations of certain chemical production centers are determined via solving a mixed integer optimization problem. The outlined case study investigated the optimal strategic planning for CBTL technologies in the UK, identifying the optimal locations for these plants that result in high profitability over the entire planning horizon.

3.3. Natural gas and biomass to liquids (BGTL)

Hybrid biomass and natural gas energy systems have not been studied as extensively as the aforementioned systems. Borgwardt

(1997) proposed a natural gas and biomass co-feeding system for methanol production, intended for fuel cell applications. The integration of biomass can reduce pollution in both the process and the products consumption. Dong and Steinberg (1997) proposed a method called the Hynol process to produce methanol with reduced CO₂ emission. The process consists of hydrogasification of biomass, steam reforming of the produced gas and natural gas feedstock, and methanol synthesis. Hydrogasification refers to the recycle of the H₂ rich gas after methanol synthesis into the gasifier so that no oxygen is needed to maintain the reactor temperature.

Li, Hong, et al. (2010) took advantage of hydrogen-rich natural gas and carbon-rich biomass to design a polygeneration system that produces methanol and electricity. By adjusting the feedstock ratio, the gas-shifting process that usually is done by a water gas shift reactor can be eliminated without cost. They found that co-feeding biomass and natural gas can reduce material inputs into the system. In Clausen, Houbak, et al. (2010), also reviewed in Section 2.3, the plant configuration that combines electrolysis of water, gasification of biomass, and autothermal reforming of natural gas for catalytic methanol synthesis yielded the lowest production cost.

Liu et al. (2011b) investigated two designs of natural gas and biomass systems that co-produce electricity and FT fuels, one in which CO₂ is vented and the other captured. The design follows the developed processes in Kreutz et al. (2008) closely, and when compared to the plant configurations in Kreutz et al. (2008) they found that the performance of the BGTL system out-competes all other systems, except for the CBTL case.

3.4. Coal, biomass, and natural gas to liquids (CBGTL)

3.4.1. Single stand-alone processes

Floudas and co-workers have proposed in a series of papers novel hybrid coal, biomass, and natural gas to liquid (CBGTL) systems (Fig. 4 reprinted from Baliban et al. (2010)) that produce gasoline, diesel, and kerosene according to the demand ratio for the US, motivated by the work of Agrawal et al. (2007). The studies on this new hybrid CBGTL process (Baliban et al., 2010; Elia et al., 2010) outline the initial process development in Aspen Plus, along with a novel gasifier stoichiometric-based mathematical model, a detailed economic analysis, and simultaneous heat and power integration for 7 different case studies (Baliban et al., 2010; Elia et al., 2010). The initial design is expanded into a CBGTL superstructure that includes alternative conversion routes from the coal, biomass, and natural gas inputs to the gasoline, diesel, and kerosene products (Baliban et al., 2011). The superstructure incorporates multiple alternative process units, stream interconnectivities, and a variety of unit operating conditions. Mixed integer nonlinear optimization-based process synthesis methods are employed to identify the optimal plant topology under different scenarios. The complete superstructure is modeled mathematically, including a simultaneous heat and power integration that utilize heat engines to recover waste heat from the process and produce steam and electricity. A MINLP model is formulated and the heat and power integration is performed simultaneously along with the process synthesis step.

This MINLP model is further extended in Baliban et al. (2012) to also include a complete wastewater network and the determination of an efficient wastewater treatment network that minimizes freshwater consumption and wastewater discharge. A superstructure of a wastewater network is postulated that includes a biological digester and a sour stripper as options for treatment of process water streams that can have high concentrations of acidic gases and organic species and a cooling water and steam cycles uses for the heat and power integration. The mathematical model for this superstructure forms a process synthesis problem with simultaneous heat, power, and water integration. The model is tested on a total of 108 case studies which consist of combinations of six coal feedstocks, three biomass feedstocks, three plant capacities, and two plant superstructures, namely with and without carbon sequestration.

3.4.2. Supply chain networks

In Elia et al. (2011), the supply chain network problem is investigated to explore the potential of the CBGTL process to fulfill the entire United States transportation demand using domestic coal, biomass, and natural gas sources. An optimization framework was proposed to identify the optimal locations of CBGTL facilities in the United States that yield the lowest cost of fuel production. The supply chain starts at the feedstock source locations and ends at the demand locations. The considered CBGTL plant designs were obtained from the Aspen Plus simulations and analyses based on Baliban et al. (2010) and Elia et al. (2010), using distinct combinations of 6 coal species, 15 biomass species, 1 natural gas composition, and 3 plant capacities. The model takes into account the layout of feedstock availabilities in the United States, demand locations, existing transportation infrastructure, and the costs associated with each segment of the energy supply chain. It was shown that the CBGTL process can fulfill the United States transportation demand with costs that are competitive with petroleum-based processes and significant reduction in greenhouse gas emissions (Elia et al., 2011).

4. Research groups contributions

Table 6 presents a representative list of the research contributions on single feedstock and hybrid feedstock energy processes organized by research groups worldwide.

5. Future challenges and opportunities

Based on the studies present in literature, the following challenges and opportunities are highlighted for the single feedstock and hybrid feedstocks energy processes:

- **Hybrid feedstock energy processes.** Further development of hybrid feedstock energy processes can be pursued in the future. Based on the current simulation studies, optimization based process synthesis approaches are important tools in designing efficient hybrid systems with multiple feedstocks and technologies. Additional integration with other renewable sources can be explored, such as electricity or hydrogen from wind and solar sources.
- **BGTL process.** The combined natural gas and biomass energy systems have not been extensively studied. This particular hybrid system can potentially be useful, especially for the United States transportation sector, due to the growing interest in biomass utilization and abundant natural gas reserves in the country.
- **Water integration.** Few works have considered the water integration approach in the development of both the single feedstock and hybrid feedstocks energy processes to minimize the consumption of freshwater. This area is an important aspect of energy system designs since pressure on water resources is projected to increase in the future as population and the consumption from domestic, agricultural, and industrial usage increase. Efficient water usage in energy processes is necessary, especially since the utilization biomass will also increase water consumption for its cultivation. Process systems engineering is able to address this problem via optimization-based wastewater network synthesis.
- **Supply chain and facility location problem.** The supply chain analysis and the facility location problem for the hybrid feedstock energy processes need to be further developed. Although coal and natural gas supply chain problems are less relevant than biomass (see Table 2), the incorporation of biomass in energy systems will then require a consideration of the availability and distribution of the feedstock. The CBTL and BGTL facility location problems will elucidate the areas where the plant distances to coal, natural gas, and biomass sources, as well as the fuel market are optimal. Similarly for the CGTL process, insights can be gained on the tradeoffs between placing facilities close to the coal or natural gas resources.
- **Facility location of polygeneration systems.** As many studies have pointed out the economic benefit of polygeneration systems, researchers can explore the facility location problem for such systems with multiple market sectors taken into consideration. So far, most studies have performed the supply chain analysis for the fuel market. However, when the conversion technologies also co-produce electricity, heat, hydrogen, etc., these other markets, which may have different geographical configuration than the fuel market, need to be taken into account and will affect the optimal locations of the polygeneration plants.
- **Strategic planning.** The strategic planning problem for both the single feedstock and the hybrid feedstocks energy processes is an opportunity for researchers to investigate the long-term viability of each system. Either one type or multiple type of plants can be considered (i.e., a network in which a combination of the single and hybrid systems is included) for a certain region or country. Where specific geographical locations are considered, different

Table 6
Hybrid energy systems contributions on complete stand-alone processes and energy supply chain networks organized by research groups.

Groups	Affiliations	Country	CTL	GTL	BTL	CGTL	CBTL	BGTL	CBGTL
Agrawal et al.	Purdue University	USA	X		X				
Barton et al.	Massachusetts Institute of Technology	USA	X		X	X			
Bertuccio et al.	University of Padova	Italy	X	X		X			
Bezzo et al.	University of Padova	Italy			X				
Borgwards	US Environmental Protection Agency	USA						X	
Bridgwater et al.	Aston University	UK			X				
Brown et al.	Iowa State University	USA			X				
Chang et al.	South China University of Technology	China			X				
Cherubini, F.	Norwegian University of Science and Technology	Norway			X				
Clausen et al.	The Technical University of Denmark	Denmark			X				
Cocco et al.	University of Cagliari	Italy	X						
Cundiff et al.	Virginia Polytechnic Institute and State University	USA			X				
Daoutidis et al.	University of Minnesota	USA			X				
Dooley et al.	Pacific Northwest National Laboratory	USA	X						
Dowaki et al.	Mid-Sweden University	Sweden			X				
Eden et al.	Auburn University	USA			X				
Eksioglu et al.	Mississippi State University	USA			X				
El-Halwagi et al.	Texas A&M University	USA		X	X		X		
Faaij et al.	Utrecht University	The Netherlands	X	X	X				
Fan et al.	University of California, Davis	USA			X				
Floudas et al.	Princeton University	USA	X		X				X
Gao et al.	Chinese Academy of Sciences	China	X	X					
Gorgens et al.	Stellenbosch University	South Africa			X				
Grossmann et al.	Carnegie Mellon University	USA			X				
Gustavsson et al.	Mid-Sweden University	Sweden			X				
Hall	Texas A&M University	USA		X					
Han et al.	Seoul National University	South Korea		X					
Hansson et al.	Swedish University of Agricultural Sciences	Sweden			X				
Hao et al.	Chinese Academy of Sciences	China		X					
Henrich et al.	Karlsruhe Institute of Technology	Germany			X				
Hu et al.	Tsinghua University	China	X	X		X			
Huffman	University of Kentucky	USA	X						
Jaramillo et al.	Carnegie Mellon University	USA	X	X					
Jin et al.	Chinese Academy of Sciences	China		X				X	
Jun et al.	Korea Institute of Energy Research	South Korea		X					
Karimi et al.	National University of Singapore	Singapore		X					
Kjelstrup et al.	Norwegian University of Science and Technology	Norway		X					
Kokossis et al.	National Technical University of Athens	Greece			X				
Kreutz et al.	Princeton University	USA	X	X	X		X	X	
Kumar et al.	University of Alberta	Canada			X				
Larson et al.	Princeton University	USA	X	X	X		X	X	
Leduc et al.	Lulea University of Technology	Sweden			X				
Li et al.	Chinese Academy of Sciences	China	X						
Liu et al.	Tsinghua University	China	X			X	X		
Lynd et al.	Dartmouth College	USA			X				
Manganaro et al.	Stevens Institute of Technology	USA		X					
Marechal et al.	Ecole Polytechnique Fédérale de Lausanne	Switzerland			X				
Minowa et al.	National Institute at Advanced Industrial Science and Technology	Japan			X				
Ouyang et al.	University of Illinois at Urbana-Champaign	USA			X				
Papageorgiou et al.	University College London	UK			X				
Parker et al.	University of California, Davis	USA			X				
Perales et al.	Universidad de Sevilla	Spain			X				
Pistikopoulos et al.	Imperial College London	UK	X			X	X		
Ptasinski et al.	Eindhoven University of Technology	The Netherlands			X				
Realff et al.	Georgia Institute of Technology	USA			X				
Renó et al.	Federal University of Itajubá	Brazil			X				
Romagnoli et al.	Louisiana State University	USA			X				
Rubin et al.	Carnegie Mellon University	USA	X						

Table 6 (Continued)

Groups	Affiliations	Country	CTL	GTL	BTL	CGTL	CBTL	BGTL	CBGTL
Sadhukhan et al.	University of Manchester	UK			X				
Shah et al.	Imperial College London	UK			X				
Song et al.	Seoul National University	South Korea		X					
Steinberg et al.	Brookhaven National Laboratory	USA						X	
Tatsiopoulos et al.	National Technical University of Athens	Greece			X				
Tiffany et al.	University of Minnesota	USA			X				
van der Berg et al.	University of Twente	The Netherlands	X	X					
Weidou et al.	Tsinghua University	China	X						
Wilhelm et al.	Texas A&M University	USA			X				
Williams et al.	Princeton University	USA	X	X	X		X	X	
Wu et al.	Argonne National Laboratory	USA			X				
Wu et al.	Curtin University of Technology	Australia			X				
Xiao et al.	Southeast University	China			X				
Ying et al.	East China University of Science and Technology	China	X						
Yoon et al.	Seoul National University	South Korea			X				
Zhao et al.	Purdue University	USA			X				
Zheng et al.	Tsinghua University	China	X						
Zwart et al.	Energy Research Centre of The Netherlands (ECN)	The Netherlands			X				
<i>Government reports</i>									
Black et al.	National Energy Technology Laboratory	USA	X	X					
Tarka et al.	National Energy Technology Laboratory	USA	X		X		X		
Reed et al.	National Energy Technology Laboratory	USA	X						
Phillips et al.	National Renewable Energy Laboratory	USA			X				
Jones et al.	Pacific Northwest National Laboratory	USA			X				
–	Bechtel	USA	X		X				

sites will have different resource profiles. Thus, the design of the energy system suitable for a particular location will be distinct from the others. Uncertainties can further be incorporated into the problem to account for variety and fluctuations in any process and supply chain parameters.

- **Uncertainty.** For long-term energy planning, it is important to take uncertainties in demand, supply, and price parameters into account to assure the robustness of the planning solutions for the future. Uncertainty considerations for both single feedstock processes and hybrid feedstock processes, for (i) the design of stand-alone processes, and (ii) the design of an energy supply chain networks have not been investigated extensively, providing opportunities for the advancement of research in energy processes.

6. Conclusions

This review paper has outlined the contributions for single feedstock and hybrid feedstocks energy systems, based on indirect liquefaction of coal, natural gas, and biomass via syngas intermediates, and includes studies on the stand-alone systems and network-based supply chain and facility location analyses. The main products considered are gasoline, diesel, kerosene, methanol, and DME, with optional co-production of electricity, hydrogen, and LPG. Future opportunities are outlined, highlighting the development of stand-alone hybrid feedstock energy systems and their supply chain considerations to achieve performance synergy for the future energy market.

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